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RESEARCH MEMORANDUM

EXPERIMENTAL AND ANALYTICAL STUDY OF BALANCED-DIAPHRAGM FUEL DISTRIBUTORS FOR GAS-TURBINE ENGINES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EXPERIMENTAL AND ANALYTICAL STUDY OF BALANCED-DIAPHRAGM FUEL DISTRIBUTORS FOR GAS-TURBINE ENGINES

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SUMMARY

A method of distributing fuel equally to a plurality of spray nozzles in a gas-turbine engine by means of balanced-diaphragm fuel distributors is presented. The experimental performances of three of eight possible distributor arrangements are discussed. An analysis of all eight arrangements is included. Criterions are given for choosing a fuel-distributor arrangement to meet specific fuel-system requirements of fuel-distribution accuracy, spray-nozzle pressure variations, and fuel-system pressures.

Data obtained with a model of one distributor arrangement indicated a maximum deviation from perfect distribution of 3.3 percent for a 44 to 1 range (19.5 to 862 lb/hr) of fuel-flow rates. The maximum distributor pressure drop was 125 pounds per square inch. The method used to obtain the required wide range of flow control in the distributor valves consisted in varying the length of a constant-area flow path.

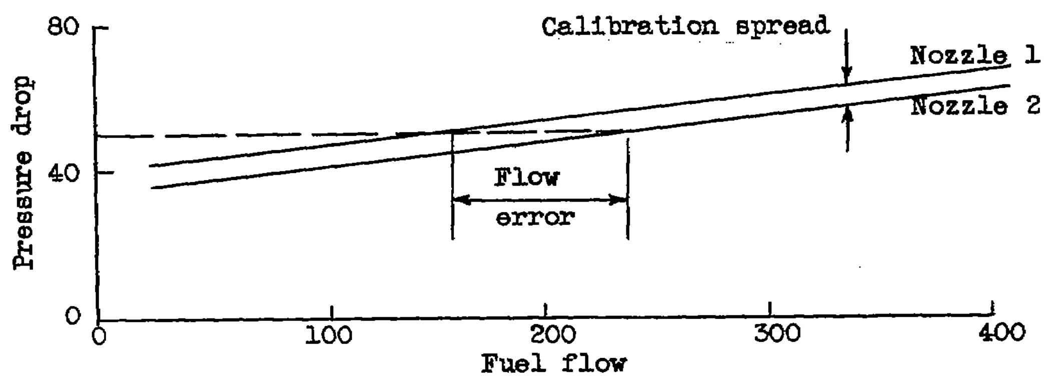
INTRODUCTION

The problem of supplying liquid fuel to a plurality of fuel-spray nozzles in gas-turbine engines has become more difficult as operating ranges have widened. Fine atomization must be provided over a wide range of fuel-flow rates to obtain high efficiencies in the combustion chamber. Excessive fuel-system pressures must also be avoided. Spray-nozzle pressure characteristics that meet these requirements introduce the additional problem of maintaining uniform fuel distribution to the plurality of nozzles.

With simple fixed-area fuel nozzles (reference 1) fed by a manifold, very low pressure drops must be employed in the low flow range in order to avoid excessive fuel-system pressures in the high flow range. With low pressure drops, however, the differences in elevation of the nozzles have a marked detrimental effect on the fuel distribution. In addition, low nozzle-pressure drops result in poor atomization of the fuel.

The double-manifold duplex-nozzle system (reference 1), which was introduced as a means of obtaining wider flow-rate ranges with reduced pressure ranges, alleviates the elevation effects at very low flow rates but not at intermediate flow rates where the flow through the secondary slots is small. The possibility of back flow from one nozzle swirl chamber to another through the secondary manifold also necessitates accurate matching and introduces a degree of uncertainty as to fuel distribution accuracy after the nozzles have been in service on the engine. 1349

The single-inlet duplex nozzle (reference 2) eliminates the possibility of back flow but requires the use of closely matched spring-loaded valves. Slight shifts in spring position or slight differences in spring set make the matching of this type of nozzle very difficult. Matching of the single-inlet multiplex nozzle, or variable-area nozzle (reference 3), becomes physically impossible when wide flow-rate ranges (in excess of 20 to 1) are desired with very narrow pressure ranges (2 to 1). The problem of matching low-pressure-rise variable-area spray nozzles is illustrated by the following figure where the calibration of two hypothetical spray nozzles are indicated:



When both nozzles are operated at the same pressure as indicated by the dashed line, the flow error is very large in spite of the small calibration difference. If a greater slope of the calibration curve can be tolerated the flow error is reduced.

The vaporizing-type of burner fuel system presents virtually the same distribution problem as the simple fixed-area-nozzle fuel system. Low pressure drops across the metering orifices at low flow rates introduce serious errors due to differences in elevation of the points of liquid-fuel entry.

A practical approach to the solution of these spray-nozzle problems is the application of a separate device for maintaining fuel distribution independently of spray-nozzle-flow resistances. The removal of the metering function from the spray nozzle allows greater freedom in spray-nozzle construction, and therefore improved fuel atomization, and reduced maximum fuel-system pressures. A study of possible means of controlling fuel distribution to several nozzles in a manner that would be independent of nozzle-flow resistances was therefore started in 1945 at the NACA Lewis laboratory. The method selected is based on the control of pressure differentials across fixed orifices. Experimental bench results obtained with a basic fuel distributor that supplies four spray nozzles operating on this principle were reported in 1946 in a now unavailable report. This report was later reissued (reference 4). The results of an investigation of a basic fuel distributor that feeds 14 fixed-area fuel nozzles on a bench and on a gas-turbine engine are reported in reference 5. Use of a distributor having a modified pilot system for feeding 14 variable-area fuel nozzles in an engine is reported in reference 3. In the present report the modified pilot system is termed "a self-setting pilot".

This report presents a summation of the fuel distributor bench results included in references 3, 4, and 5 and, in addition, includes experimental bench data on a new fuel distributor arrangement which feeds 10 variable-area nozzles that have a much wider range of fuel-flow rates. Analyses are presented of the eight possible distributor arrangements obtained by combinations of fixed-area and variable-area components and the basic and the self-setting pilot systems. Some distributor application considerations are also treated.

APPARATUS AND METHOD

Basic Fuel Distributor

The simplest arrangement for distributing fuel to various spray nozzles by the principle of controlling pressure differentials across fixed orifices is schematically shown in figure 1. Fuel is delivered to the distributor under pressure through the inlet and fills the manifold passage. From the manifold passage the fuel flows into the individual manifold branches through the matched metering jets and the diaphragm-operated equalizing valves to the individual-branch spray nozzles. Fuel also flows from the manifold passage into the pilot branch, through the pilot metering jet and the regulator jet, to the pilot spray nozzle. The pilot spray nozzle is the same as the branch spray nozzles and is also used to supply fuel to the engine. 1349

By means of the pressure-equalizing passage, the static pressures in the individual chambers A are maintained equal. The control diaphragms that separate chambers A and B position the equalizing valves until the pressure in chambers B are equal to the pressures in chambers A.

If the branch spray-nozzle pressures are equal to the pilot spray-nozzle pressure, the static-pressure drop across each equalizing valve will be equal to the static-pressure drop across the regulator jet. The open area of the equalizing valves will then be proportional to the area of the regulator jet. If any one branch spray-nozzle pressure should rise above the pilot spray-nozzle pressure, the equalizing valve in the branch supplying that nozzle would have a reduced static-pressure drop and would move to a position of larger opening. If, on the other hand, any one branch spray-nozzle pressure should fall below the pilot spray-nozzle pressure, the reverse would occur. In either case, the static-pressure drop across the branch metering jet remains equal to the drop across the pilot metering jet and the quantitative distribution of fuel is undisturbed.

A test model of the basic distributor was constructed substantially as shown schematically in figure 1. Photographs of the model are shown in figure 2, where figure 2(a) shows an assembled distributor and figure 2(b) shows a disassembled view of a section for feeding fuel to two spray nozzles.

Modifications of Basic Distributor

Self-setting pilot. - As subsequently shown, there is considerably more latitude in range of controllable spray-nozzle pressures for the basic distributor when the branch spray-nozzle pressures are below the pilot spray-nozzle pressure than when the branch spray-nozzle pressures are above the pilot spray-nozzle pressure. It is therefore desirable to set the pilot spray-nozzle pressure slightly above the highest expected branch spray-nozzle pressure. The highest branch spray-nozzle pressure that will exist during operation is, however, difficult to anticipate with spray nozzles that are subject to variations in their pressure levels, such as variable-area spray nozzles. Furthermore, the pressure level of the pilot spray nozzle may fall whereas the pressure level of the branch spray nozzles may rise. The addition of a means for automatically setting the resistance of the pilot spray nozzle to equal the highest resistance of the branch spray nozzles becomes essential if the proper performance of the distributor is to be assured. The term "self setting" is applied to this type of distributor.

A self-setting distributor employs a springless diaphragm-operated-pilot resistance valve, located in the pilot branch upstream of the pilot spray nozzle, that is automatically vented by a multiple pressure selector to the branch line feeding the spray nozzle having the highest resistance. As schematically shown in figure 3, each branch line feeding a nozzle is vented to a diaphragm-operated check valve. If the pressure in one of the branch lines is higher than the pressure being transmitted to the opposite port of the check valve, the check-valve diaphragm is moved upward as shown in the center branch of figure 3 and the branch pressure is transmitted downward. If the pressure in the branch line is lower than the pressure transmitted to the opposite port of the check valve, the diaphragm is moved downward, and the higher pressure entering the upper port is transmitted downward. In this manner, the highest pressure existing in any of the branch lines is transmitted downward to chamber C. The diaphragm-operated pilot resistance-valve positions itself to maintain the pressure in chamber D equal to that in chamber C. The regulator jet therefore always discharges into a pressure equal to that existing in the branch line feeding the nozzle whose resistance is highest. In the event the pilot spray nozzle should have the highest resistance, the pilot resistance valve moves to a wide-open position and the regulator jet again discharges into a pressure equal to that existing in the branch line feeding the nozzle with the highest resistance.

A test model of the self-setting distributor was constructed substantially as schematically shown in figure 3. A photograph of the model is shown in figure 4.

<u>Variable-area regulator jet.</u> - The basic and self-setting distributors described have fixed-area regulator jets. Because the pressure drop across a fixed-area jet varies as the square of the flow rate, the pressure drop at high flow rates may be excessive when a satisfactory pressure drop is used for the minimum flow rate. Substitution of a variable-area regulator jet would improve this condition. The pressure drop across a variable-area regulator jet can be made a linear function of fuel-flow rate and can be a nearly constant value.

The variable-area pilot regulator jet is shown in figure 5 as a spring-loaded valve. The pressure differential across the valve acts on the area of the movable member, opening the valve against the spring tension. For each fuel-flow rate there is one value of open area of the valve and one value of pressure drop.

The variable-area regulator jet was added to the self-setting distributor model previously discussed.

<u>Variable-area metering jets.</u> - The area of a fixed-area metering jet is selected on the basis of the minimum pressure drop that can be controlled accurately by the equalizing valves. For very wide fuel-flow ranges, where excessive pressure drops may occur at the high flow rates, variable-area metering jets are necessary. The flow pressure-drop relation of the variable-area metering jets is substantially linear and the maximum pressure drop can be kept at a reasonably low value.

A schematic diagram of a method of incorporating variable-area metering jets in a distributor is shown in figure 6. Metering orifices are drilled in the sides of the inlet manifold and a sliding sleeve fits inside the manifold with drilled holes mating the holes in the manifold. The sliding sleeve is operated by a diaphragm vented to the downstream pressure of the pilot metering jet. The pressure in the manifold acts on the diaphragm against a spring load and the vent pressure to move the sleeve and increase the open area of the metering jets upon increase in pressure differential across the diaphragm.

A variable-area metering-jet unit containing four jets was constructed in order to study the accuracy of fuel metering by this modification. A schematic diagram of the variable-area metering-jet unit is shown in figure 7.

Distributor combinations. - Several other combinations of distributor modifications are possible (for example, a basic distributor with variable regulator and metering jets). The symbols defined in appendix A are used in an analysis of characteristics of
1349 eight possible distributor combinations given in appendix B.

BENCH APPARATUS

The bench apparatus used for investigating the performance of the fuel distributors is shown schematically in figure 8. The total flow to the distributors was controlled by a throttle valve in the supply line. Fuel-flow rates to each spray nozzle were measured with rotameters. A rotameter covering a range of 15 to 150 pounds per hour was connected in series with a rotameter having a range of 100 to 500 pounds per hour. Above 500 pounds per hour the bench connections were so arranged that two 100-to-500-pound-per-hour rotameters were connected in parallel, which allowed a maximum measurable fuel flow of 1000 pounds per hour per nozzle. The pressure drop across the distributor components was measured by manometers for low values (up to 100 inches of fuel) and with calibrated pressure gages for high values.

The variable-area metering-jet unit was calibrated with air on an orifice comparator and the four holes were matched by polishing with crocus cloth to obtain equal flow rates at the positions of maximum area. Other area settings were obtainable by adjusting the inner sleeve position (fig. 7) by means of the adjusting screw. The holes were maintained in line by means of an alining pin and the position of the inner sleeve was indicated by a dial indicator reading to 0.0001 inch.

A schematic diagram of the bench apparatus for calibration of the variable-area metering jets with fuel is shown in figure 9. Fuel enters the housing and flows through the metering jets. The flow rate through each of the four lines was measured by rotameters. The pressure differential across the jets was measured by an inverted U-tube for low pressure drops and a mercury U-tube for high pressure drops. Pressure differential across the metering jets was controlled by means of valves installed in each line downstream of the jet. The downstream pressure on each metering jet was indicated by a bank of manometer tubes installed as shown in figure 9. Pressure drop, fuel flow, and sleeve position were obtained for each variable-area metering jet for each calibration point.

The fuel used for all bench investigations was AN-F-32.

Rotameter accuracy. - Accuracy of flow measurement is an important consideration in determining the accuracy of control of flow rates. Rotameters have an inherent possible error of 1 percent of the full-scale reading. For example, a rotameter covering a range of 15 to 150 pounds per hour would have a possible random error of 1 percent of 150, or 1.5 pounds per hour. This error may exist at a reading of 15 pounds per hour, at which point the percentage error would be 10 percent possible random error. This possible random rotameter error must be considered in a study of the data to be presented. 1349

RESULTS AND DISCUSSION

Basic Distributor

The basic distributor model investigated was used to feed 14 mismatched fixed-area fuel-spray nozzles selected to give a difference in flow among the nozzles of ±10 percent at the same pressure drop. The accuracy of fuel distribution obtained from this basic distributor when feeding these 14 nozzles is shown in figure 10. Above a flow rate of 100 pounds per hour per nozzle, the maximum deviation from perfect distribution was 3.5 percent. Below 100 pounds per hour per nozzle, the fuel distribution became less accurate and reached a maximum of 7.5 percent deviation from perfect distribution at the minimum flow rate of 33 pounds per hour. At this flow rate a possible rotameter error of 4.6 percent exists, as indicated by the dashed lines in figure 10. The break in the dashed lines at 150 pounds per hour indicates the transfer point of flow indication from one rotameter size to another.

The marked departure of the fuel distribution from perfect distribution at the low flow rates is attributed to failure of the equalizing valves to accurately control the downstream pressure of the metering jets. Inasmuch as the basic distributor has a fixed-area regulator jet, the pressure drop across the equalizing valve is low at low flow rates. In the event of departure of a spray-nozzle pressure from the rated pressure, only a small transient pressure differential exists to act on the equalizing valve diaphragm to move the valve to a new position. The force created by the small pressure differential may not be sufficient to completely overcome the friction forces of the piston sliding in the valve sleeve.

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The pressure drop across the basic distributor is shown in figure 11. Data are presented for the pressure drop across both the metering jet and the regulator jet; the distributor pressure drop is the sum of the pressure drops across the two jets. The maximum pressure drop is 70 pounds per square inch at a flow of 300 pounds per hour, which is not excessive for the narrow range (9 to 1) of fuel-flow rates covered. If the range of fuel flows were substantially increased, however, the maximum pressure drop would become very great.

The range of controllable spray-nozzle pressures is shown in figure 12. These data were obtained by substitution of a needle valve in place of one of the fixed-area spray nozzles. The needle valve was adjusted in successive increments from substantially zero-flow resistance to a flow resistance where the equalizing valve in that line became inoperative at its wide-open position. The distributor maintained a substantially constant fuel-flow through the needle valve over the full range of flow resistance from 0 to 1.46 times the rated spray-nozzle resistance at all fuel-flow rates. The basic distributor will therefore distribute fuel to spray nozzles having resistances equivalent to any value within the shaded area of figure 12 with the accuracy shown in figure 10.

Modifications of Basic Distributor

Self-setting distributor. - The self-setting distributor model investigated was used to feed 14 variable-area fuel-spray nozzles. The calibration spread of the nozzles used is shown in figure 13, where the dashed line illustrates the condition of severe mismatching. At a pressure drop of 55 pounds per square inch, one nozzle will flow 58 pounds of fuel per hour and another nozzle will flow 240 pounds per hour. Fuel-distribution accuracy of this self-setting distributor feeding the 14 fuel nozzles is shown in figure 14. Above a fuel-flow rate of 100 pounds per hour per nozzle the maximum deviation from perfect distribution is 2.8 percent. Below 100 pounds per hour the maximum deviation is 5.6 percent. Comparison of these data with that of figure 10 indicates only slight improvement in distribution accuracy above that of the basic distributor. As previously discussed for the basic distributor, the inaccuracy at low flow rates is due to equalizing valve positioning errors, which result from the low pressure drop across the fixed-area regulator jet.

The pressure drop across the model of the self-setting distributor investigated is the same as that of the model of the basic distributor shown in figure 11.

The range of spray-nozzle pressures that can be compensated by the self-setting distributor is limited only by the minimum area of the equalizing valve in the branch line feeding the nozzle with the lowest pressure drop. The range of spray-nozzle pressures that can be compensated by the self-setting distributor model investigated is shown in figure 15. The controllable range of spray-nozzle pressures for this distributor was calculated from the actual dimensions of the equalizing valve used. For the higher flow rates, it is apparent that an extremely wide range exists. At lower flow rates, however, a limited range exists, and at 20 pounds per hour per branch line the controllable range is just sufficient to compensate for the normal variation of variable-area spray-nozzle resistances. The improvement in range of controllable nozzle pressures by use of a self-setting distributor in place of a basic distributor is apparent from comparison of figures 15 and 12. For example, at a flow rate of 120 pounds per hour the self-setting distributor (fig. 15) will control the flow to spray nozzles having a difference of 600 pounds per square inch pressure drop compared with a difference of 32 pounds per square inch between nozzle pressure drops for the basic distributor (fig. 12).

Variable-area regulator jet. - Ten variable-area fuel-spray nozzles with a 45 to 1 range of fuel-flow rates were fed by the experimental model of the self-setting, variable-area regulator-jet distributor. The calibration spread of the 10 nozzles is shown in figure 16 and the unmatched condition of these nozzles is illustrated by the dashed line. At a pressure drop of 52 pounds per square inch, one nozzle will flow 100 pounds of fuel per hour and another nozzle will flow 450 pounds of fuel per hour. Distribution-accuracy data for a 44 to 1 fuel-flow range were obtained with the distributor feeding these nozzles (fig. 17). This 44 to 1 range represents an increase of approximately four times the useful range of the basic distributor. For a range of flow rates from 93 to 862 pounds per hour per nozzle the maximum deviation from perfect distribution was 2.2 percent. Above 90 pounds per hour, 75 percent of the data are within 1.5 percent of perfect distribution. The maximum deviation from perfect distribution is 3.3 percent and occurs at the minimum flow rate of 19.5 pounds per hour.

The improvement in accuracy of the self-setting, variable-area regulator-jet distributor over the basic and self-setting distributors is apparent from comparison of figures 10, 14, and 17. For example, at 33 pounds per hour the fuel distribution error is reduced from 7.5 to 2.8 percent.

The improvement in accuracy over the wider flow range is attributed directly to the use of the variable-area regulator jet. The flow-pressure-drop relations of the self-setting variable-area
1349 regulator jet distributor are shown in figure 18. At the minimum flow rate of 19.5 pounds per hour, the pressure drop across the regulator jet is 11 pounds per square inch compared with 0.27 pound per square inch for a fixed-area regulator jet. Because the distributor sets up a similar pressure drop across the equalizing valves, a sufficient transient-pressure differential on the equalizing-valve diaphragm is produced, which overcomes the friction forces of the valve piston sliding in the sleeve in the event a new valve position is required.

The maximum pressure drop across the self-setting distributor with a variable-area regulator jet (fig. 18) is 125 pounds per square inch at the maximum fuel flow for the 44 to 1 range of fuel-flow rates as compared with 65 pounds per square inch at the maximum fuel flow for the 10 to 1 range of the basic distributor. The metering jet contributes more to the maximum distributor pressure drop than the regulator jet. A substantial improvement over the basic and self-setting distributors is indicated by comparison of figures 11 and 18.

The range of spray-nozzle pressures that can be compensated by the distributor was computed from the dimensions of the equalizing valve and is shown in figure 19. This distributor will distribute 14 pounds of fuel per hour to each of several spray nozzles having a maximum difference of 800 pounds per square inch pressure drop. The self-setting distributor will distribute the same fuel-flow rate equally to spray nozzles with a maximum difference of only 7 pounds per square inch (fig. 15). The substantial improvement in range afforded by the variable-area regulator-jet distributor is due to the use of a variable length of flow path in the equalizing valves (discussed in appendix C), which results in a very small minimum valve effective area. The variable-area regulator jet sets a finite limit greater than zero fuel flow due to the initial spring load below which the distributor will not function. This limit for the model investigated is about 1.5 pounds per hour, which is below the range of fuel-flow rates used for the investigation.

Variable-area metering jets. - Data obtained from investigation of the variable-area metering-jet unit are shown in figure 20. The effective areas of the four jets are plotted as a function of the fuel-flow rate through each jet. The connected data points were taken with the same setting of actual metering-jet area at various pressure drops. The pressure drops are indicated by the radial lines.

The slight decrease of effective area as the fuel flow is increased indicates a decrease in the flow coefficient as the pressure drop is increased. The percentage values presented in figure 20 are the maximum area deviations from the mean of the four areas at the pressure drop where the greatest variation between the four areas exists. It is obvious from figure 20 tha the four jets are not perfectly matched, with maximum variations of as much as 16.2 percent and -10.0 percent at small area settings. It is believed, however, that the jets could have been more accurately matched by improved fabrication technique. Jet number 2, for example, has a smaller effective area than the other jets at every area setting and it is possible that the percentage deviation could be reduced by increasing the size of this jet. 1349

The dashed line in figure 20 represents a typical operating curve for a variable-area metering-jet unit installed in a distributor from which the fuel-flow rate, the effective area, and the pressure drop may be determined. The position of the operating curve at the minimum fuel-flow rate is determined by a compromise between small areas where large area errors occur and low pressure drops where control of the pressure drop is less accurate. Data presented near the operating curve in figure 20 indicate an accuracy of 3.3 and -3.2 percent along the dashed line. It is believed that an accuracy of ±2 percent can be achieved for an operating curve by improved fabrication technique. This accuracy is somewhat less than can be obtained from fixed-area metering jets where ±1 percent has been obtained. The maximum pressure drop across variable-area metering jets, however, may be greatly reduced compared with fixed-area metering jets for very wide ranges of fuel-flow rates.

Vibration

During the bench runs of the distributor models, the effect of vibration on distributor performance was determined by vibrating the distributor with an air-operated mechanical vibrator. Vibration had little effect on performance except at branch flow rates below 100 pounds per hour where the distribution accuracy was slightly improved. The fuel-distribution data obtained in engine tests of two distributors (references 3 and 5) indicated that engine vibration also caused a slight improvement in distributor performance.

Distributor Selection

In order to select a fuel distributor to meet specific fuel-system requirements, a study of the requirements must be made. Factors that must be considered are: the flow range required, the fuel pressures available, the accuracy desired, and the range of spray-nozzle pressures that must be compensated. By using various combinations of fixed-area and variable-area metering and regulator jets with the basic or self-setting distributor, eight combinations are possible. Mathematical expressions for distributor operation, range of spray-nozzle pressures, and distributor pressure drops for these combinations are given in appendix B. A discussion of distributors suitable for feeding fixed-area and variable-area spray nozzles is also included.

The final selection of a fuel distributor must be a compromise to meet the requirements of a given application. For example, a self-setting, variable-area regulator jet distributor was found most satisfactory for a 50 to 1 range of fuel-flow rates, but excessive fuel-system pressures would result for a 100 to 1 range of fuel-flow rates. For a 100 to 1 range of fuel-flow rates, a distributor with variable-area metering jets would have to be used in spite of the probable poorer accuracy of distributing fuel. Another consideration in the application is the area range of the distributor equalizing valve, which may be as great as 241 to 1; such a range presents a valve problem. A useful principle for obtaining a wide-range valve consists of the control of flow rates by varying the length of a constant-area flow path. A comparison made between a variable-length and a variable-area valve indicated that the minimum area required for a variable-length valve was more than 10 times the minimum area required for a variable-area valve for the same conditions. These and other considerations are discussed in appendix C.

CONCLUSIONS

A performance study of balanced-diaphragm-type fuel distributors showed that no one distributor was best for all applications and a compromise was necessary depending on the following factors: flow range required, fuel pressure available, accuracy desired, and the range of spray-nozzle pressures to be compensated. For example, variable-area metering jets were found less accurate than fixed-area jets but the maximum pressure drop was considerably reduced for very wide (100 to 1) ranges of fuel flow rates.

Improvements in distributor performance were obtained by modifications of the basic distributor. The addition of a self-setting pilot to this distributor greatly increased the range of controllable spray-nozzle pressures. Replacing the fixed-area regulator jet with a variable-area regulator jet resulted in improved distribution accuracy and greatly reduced the maximum pressure drop. A model of a self-setting distributor with a variable-area regulator jet distributed fuel from 19.5 to 862 pounds per hour per nozzle (44 to 1 range) to 10 variable-area nozzles with a maximum deviation from perfect distribution of 3.3 percent. The maximum fuel-distributor pressure drop was 125 pounds per square inch. The wide range of flow control in the valves of this distributor was obtained by varying the length of a constant-area flow path. 1349

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APPENDIX A

SYMBOLS

1349 The following symbol notations are used in the analysis given in appendixes B and C:

A effective flow area (actual area times flow coefficient), sq in.

C opening pressure of spring-loaded flow device, lb/sq in. gage

g gravitational constant, 32.2 ft/sec^2

J dimensional constant in flow equation (for AN-F-32 fuel, $J = 5.88 \times 10^{-5}$), $\left(\dfrac{1}{n\sqrt{2g\rho}}\right)$, $\dfrac{\text{hr in.}}{\sqrt{\text{lb}}}$

K pressure-rise coefficient of spring-loaded flow device, hr/in.^{2}

N ratio of maximum to minimum effective area $= \dfrac{A_{max}}{A_{min}}$

n unit conversion factor, $\dfrac{3600}{12} = 300$ (sec/hr)(ft/in.)

ΔP pressure drop, lb/sq in.

W branch flow, lb/hr

ρ density of fuel, lb/cu ft

Subscripts:

b branch metering jet

c fuel distributor

e fuel nozzle

m pilot metering jet

p pilot fuel nozzle

r pilot regulator jet

v equalizing valve

s pilot resistance valve

max maximum 1349

min minimum

R rated

APPENDIX B

ANALYSIS OF FUEL DISTRIBUTOR ARRANGEMENTS

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The experimental fuel-distributor models consisted of a basic distributor and three modifications to the basic distributor. It is possible to construct eight combinations of basic and modified forms of the distributor. As will be discussed in the analysis, distributors without the self-setting feature must be adjusted or preset for the particular type of spray nozzles that is to be used. Distributors without the self-setting feature are referred to as preset or PS distributors, and self-setting distributors are referred to as SS distributors.

In order to simplify the analysis the eight possible combinations are divided into two groups; the PS distributors and the SS distributors. The eight distributor arrangements are identified by the following code system:

Preset Distributors

PS	Preset with fixed-area jets (basic distributor)
PS-VR	Preset with variable-area regulator jet
PS-VM	Preset with variable-area metering jets
PS-VR-VM	Preset with variable-area regulator and metering jets

Self-Setting Distributors

SS	Self-setting with fixed-area jets
SS-VR	Self-setting with variable-area regulator jet
SS-VM	Self-setting with variable-area metering jets
SS-VR-VM	Self-setting with variable-area regulator and metering jets

Line drawings of the eight distributor arrangements are shown in figure 21.

It is desirable to operate a fuel distributor with as low a maximum pressure drop as possible consistent with good accuracy. The pressure drop across a distributor and the accuracy of fuel distribution depend on the dimensional areas of the distributor components relative to the fuel-flow rate. A maximum area limitation exists for each of the various distributor components to insure a reasonable distribution accuracy. Because of the component size limitation there is a minimum resultant distributor pressure drop. 1349

In order to establish the range of fuel-flow rates that can be equally distributed over a range of spray-nozzle and distributor pressure drops, a study of the characteristics of the distributor components is necessary.

In this analysis the pilot branch feeds one of the engine fuel-spray nozzles. Both fixed-area and variable-area fuel-spray nozzles are considered.

Preset Distributors

Distributor operation. - Under any operating condition the sum of the pressure drops through any branch is equal to the sum of the pressure drops through the pilot branch and may be expressed by the following equation:

$$\Delta P_b + \Delta P_v + \Delta P_e = \Delta P_m + \Delta P_r + \Delta P_p \tag{1}$$

The distributor functions to maintain ΔP_b in each distributor element equal to ΔP_m in the pilot element; therefore, when the distributor is within the useful range of operation, each distributor element is so operating that

$$\Delta P_v + \Delta P_e = \Delta P_r + \Delta P_p \tag{2}$$

The distributor acts by varying ΔP_v (accomplished by varying A_v) to compensate for differences in ΔP_e (caused by variations in the resistances of the various engine fuel-spray nozzles). For equal flows to each spray nozzle, the metering jets must be matched so that A_b is equal in each distributor element and also equal to A_m in the pilot element.

Range of controllable spray-nozzle pressures. - The design requirements for the regulator jet and the equalizing valves are determined from equation (2) and the anticipated variation in spray-nozzle pressures.

Rearrangement of equation (2) to solve for ΔP_v results in:

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$$\Delta P_v = \Delta P_r + (\Delta P_p - \Delta P_e) \tag{3}$$

At each value of flow rate there is a minimum value of equalizing-valve pressure drop $\Delta P_{v,min}$ based on the maximum design area $A_{v,max}$ of the equalizing valve.

The value of ΔP_e can be increased from zero to a value greater than ΔP_p but only to such a value that the right-hand member of equation (3) is no greater than $\Delta P_{v,min}$ at the flow rate considered. Spray nozzles operating at pressures above this maximum controllable nozzle pressure will operate with decreased fuel flow.

The range of controllable nozzle pressures is a linear function of ΔP_r and therefore may be altered by increasing or decreasing ΔP_r. The range of controllable nozzle pressures is also dependent on the pilot spray-nozzle pressure ΔP_p. In the event the pilot nozzle pressure ΔP_p decreases, the controllable pressure range of all the other nozzles is decreased. If ΔP_r is small relative to ΔP_p, the range of controllable nozzle pressures may be particularly small. When ΔP_p decreases beyond the controllable range of operation, fuel will continue to flow to all the nozzles but the fuel distribution will be a function of the nozzle resistances. When ΔP_p increases above the nominal value, accurate fuel distribution is maintained providing ΔP_v is not excessive beyond the point where the equalizing valve has reached its minimum design area $A_{v,min}$. An excessive distributor pressure drop may be a further limitation on the allowable increase in ΔP_p.

The area of the equalizing valve may be expressed as follows:

$$A_v = \frac{JW}{\sqrt{\Delta P_v}} \tag{4}$$

The maximum area is usually determined by a design space limitation. The minimum area is determined by substituting in equation (4) the maximum value of ΔP_v obtained from equation (3). The value $\Delta P_{v,max}$ exists when ΔP_p is at a maximum anticipated value and ΔP_e is at a minimum anticipated value. The value of ΔP_r depends on the type of fuel nozzle used and is discussed in the next section.

Spray-nozzle considerations. - Fixed-area spray nozzles have a parabolic flow-pressure-drop relationship and the pressure drop may be expressed as follows:

$$\Delta P_{p,R} = \Delta P_{e,R} = \left(\frac{J}{A_{e,R}}\right)^2 W^2 \tag{5}$$

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Variations in the resistance of the nozzles occur when the value of A_e deviates from $A_{e,R}$. The percent deviation of nozzle pressure from the rated pressure generally remains constant over the flow range; therefore, the actual pressure deviations or range of fixed-area nozzle pressures that are to be compensated is a function of the square of the flow rate. The regulator jet requirement for a distributor feeding fixed-area spray nozzles would then be a device with a pressure drop that varies as the square of the flow rate. The fixed-area regulator jet meets this requirement.

Distributors PS and PS-VM are suitable for feeding fixed-area fuel-spray nozzles provided that the higher distributor pressure drop at the maximum fuel-flow rates can be tolerated. The size of the regulator jet is selected to provide the necessary value of ΔP_r to compensate for the anticipated greatest negative value of $(\Delta P_p - \Delta P_e)$ in equation (3). The relation for computing the size of a fixed-area regulator jet is

$$A_r = \frac{JW}{\sqrt{\Delta P_r}} \tag{6}$$

Values of ΔP_r for other flow rates may be computed from equation (6) after the value of A_r has been established.

Variable-area spray nozzles have a substantially linear flow-pressure-drop relation and the pressure drop can be substantially constant. In general, the pressure drop may be expressed as follows:

$$\Delta P_{p,R} = \Delta P_{e,R} = C_{e,R} + K_{e,R}\, W \tag{7}$$

Variations in the resistance of the nozzles occur when the values of C_e and K_e deviate from $C_{e,R}$ and $K_{e,R}$. The variable-area spray nozzle is a spring-loaded device and there is no correlation between the variations of C_e and K_e and the flow rate W.

Variations of ΔP_e and ΔP_p at low flow rates may be as large as at high flow rates. The possible variations of $(\Delta P_p - \Delta P_e)$ in equation (3) is then nearly constant over the entire fuel-flow range. The regulator-jet requirement for a distributor feeding variable-area spray nozzles would then be a device with a pressure drop that is nearly constant over the fuel-flow range. This condition precludes use of a fixed-area regulator jet, but a variable regulator jet will meet the requirements.

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The expression for the pressure drop across a variable regulator jet is

$$\Delta P_r = C_r + K_r W \tag{8}$$

The constants C_r and K_r are selected to provide the necessary value of ΔP_r to compensate for the anticipated greatest negative value of $(\Delta P_p - \Delta P_e)$ in equation (3). In general, C_r establishes the value of ΔP_r at the minimum flow rate and K_r establishes ΔP_r at the highest flow rate.

Distributors PS-VR and PS-VR-VM are both suitable for feeding variable-area fuel-spray nozzles. Complete failure of a variable-area nozzle will usually result in a nozzle-pressure drop near zero. The regulator-jet pressure drop ΔP_r must be set greater than the maximum pressure drop $\Delta P_{e,max}$ among the other nozzles at the flow rate considered to maintain regulation of distribution if the pilot nozzle should fail.

<u>Metering jets.</u> - No fixed relation exists between the size of the metering jet and the other distributor components. The size is selected on the basis of range of fuel flow. The jet must be large enough to avoid cavitation and excessive pressure drop at the maximum flow, and small enough to produce a pressure drop at the minimum flow large enough to be regulated accurately by the equalizing valve.

The relation for determining the area of a fixed-area metering jet is

$$A_m = A_b = \frac{J\, W_{min}}{\sqrt{\Delta P_{b,min}}} \tag{9}$$

Values of ΔP_b for other flows may be computed from equation (9) after the value of A_b has been established.

Fixed-area metering jets may be used for limited fuel-flow ranges without excessive pressure drops. For very wide ranges of fuel-flow rate, however, a variable-area metering jet is required.

The pressure drop of a variable-area metering jet may be approximated by the following relation:

$$\Delta P_m = \Delta P_b = C_b + K_b W \tag{10}$$

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The value of C_b is determined from the minimum ΔP_b that can be regulated by the equalizing valve for good distribution accuracy. The value of K_b is determined by the maximum ΔP_b allowable at the maximum flow rate. The maximum and minimum areas of the variable metering jet are determined by the value of ΔP_b at the maximum and minimum flow rates. The area at other flow rates is a function of the value of ΔP_b as well as other design considerations, such as the shape of the variable orifice, the spring load, and the spring rate. Equation (10), however, is a reasonably close approximation of the resultant flow-pressure-drop relation.

Distributor-pressure drop. - The pressure drop across a preset distributor is defined as the difference between the inlet pressure and the rated fuel-spray-nozzle pressure. Assuming that all spray nozzles are operating at the rated value of pressure drop, it is apparent that the distributor pressure drop is the sum of the pressure drops through the pilot metering jet and the regulator jet. The distributor pressure drop is expressed as

$$\Delta P_c = \Delta P_m + \Delta P_r \tag{11}$$

Substitution of the proper relations for ΔP_m (equation (9) or (10)) and ΔP_r (equation (6) or (8)) in equation (11) will permit computation of the distributor-pressure drops for each of the preset distributors.

Self-Setting Distributors

Distributor operation. - The self-setting feature of a distributor introduces an additional resistance term in the distributor equation. This resistance term corresponds to the addition of the pilot resistance valve in the pilot branch. The operation of a self-setting distributor may be expressed by the following equation:

$$\Delta P_b + \Delta P_v + \Delta P_e = \Delta P_m + \Delta P_r + \Delta P_s + \Delta P_p \tag{12}$$

The distributor functions to maintain ΔP_b equal to ΔP_m. Equation (12) may then be rewritten as follows:

$$\Delta P_v + \Delta P_e = \Delta P_r + \Delta P_s + \Delta P_p \qquad (13)$$

The self-setting distributor acts in the same manner as a preset distributor by varying ΔP_v to compensate for differences in ΔP_e.

Range of controllable fuel-spray-nozzle pressures. - A self-setting distributor has no upper nozzle-pressure limit beyond which the distributor is out of range due to the pilot resistance valve, which matches the resistance of the pilot branch to the resistance of the branch with the highest nozzle pressure. The flow to all spray nozzles is adjusted equal to the flow to the nozzle with the highest resistance.

Rearrangement of equation (13) to solve for ΔP_v results in

$$\Delta P_v = (\Delta P_r + \Delta P_s) + (\Delta P_p - \Delta P_e) \qquad (14)$$

At each value of flow rate there is a minimum value of equalizing-valve pressure drop $\Delta P_{v,min}$ based on the maximum design area $A_{v,max}$ of the equalizing valve.

All of the values of ΔP_e greater than ΔP_p are compensated by ΔP_s through the action of the pressure selector and pilot resistance valve which comprise the self-setting feature. For values of ΔP_e greater than ΔP_p, the value of ΔP_s may be written as

$$\Delta P_s = \Delta P_{e,max} - \Delta P_p \qquad (15)$$

Substitution of equation (15) in equation (14) will result in

$$\Delta P_v = \Delta P_r + (\Delta P_{e,max} - \Delta P_e) \qquad (16)$$

The minimum value of ΔP_v will occur in the branch line feeding the nozzle with the highest pressure, that is, when ΔP_e is equal to $\Delta P_{e,max}$. Equation (16) then reduces to

$$\Delta P_{v,min} = \Delta P_r \qquad (17)$$

Equation (17) indicates that the function of the regulator jet is to provide a pressure drop across the equalizing valve to maintain it in operating range. The range of controllable nozzle pressures is not a function of the regulator jet resistance as it was in a preset distributor.

For values of ΔP_e less than $\Delta P_{e,max}$ in equation (16), regulation is maintained by the equalizing valve providing that ΔP_v is not excessive beyond the point where the equalizing valve has reached its minimum design area $A_{v,min}$. 1349

When ΔP_p is greater than ΔP_e in equation (14), the self-setting feature is inoperative and the pilot resistance valve moves to a wide-open position. The value of ΔP_s is then a function of the square of the flow rate inasmuch as the pilot resistance valve acts as a fixed-area jet in the wide-open position. In practice, the pilot resistance valve is constructed with as large a maximum area as is possible to prevent an excessive pressure drop at the maximum-flow rate.

The area of the equalizing valve is obtained from equations (4) and (14) for any desired condition.

<u>Distributor stability.</u> - Equation (17) indicates that ΔP_r need be only large enough to maintain the equalizing valve in operating range. The area of the regulator jet could be made as large as the maximum area $A_{v,max}$ of the equalizing valve. Inasmuch as $A_{v,max}$ is constant over the flow range, a fixed-area regulator jet is suitable.

Use of a fixed-area regulator jet size equal to $A_{v,max}$ may cause cycling at low flow rates (up to about 25 percent of the maximum flow rate). Because of low pressure drops across the equalizing valves at the low flow rates, large valve motions are necessary to compensate for small nozzle-pressure changes. These large motions cause overshooting, which results in the cycling of fuel flows between the pilot fuel flow and the fuel flow to the other nozzles. If a smaller fixed-area regulator jet is used to maintain a greater $\Delta P_{v,min}$ the distributor operation will be stable. Use of a smaller jet, however, will result in a higher distributor pressure drop, which may be excessive at the maximum-flow rate for wide flow ranges.

A more desirable method of overcoming the condition of instability is the use of a variable-area regulator jet. The pressure drop across the equalizing valve can be maintained at a substantial level at the low fuel-flow rates. The pressure drop at the maximum flow rate can be kept at a minimum value consistent with the maximum area of the equalizing valve. The operation of the distributor is such that the open area of the equalizing valve will increase with the fuel-flow rate when a variable-area regulator jet is used.

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<u>Spray-nozzle considerations.</u> - A self-setting distributor will permit use of any type fuel-spray nozzle. Use of variable-area spray nozzles will require, in general, a greater equalizing valve-area range than fixed-area nozzles because they have a larger possible pressure variation at the low flow rates.

<u>Metering jets.</u> - Because there is no fixed relation between the size of the metering jet and the other distributor components, either fixed-area or variable-area metering jets may be used.

<u>Distributor-pressure drop.</u> - The pressure drop across a self-setting distributor is defined as the difference between the inlet pressure and the highest fuel-spray-nozzle pressure. It is apparent that the pressure drop is the sum of the pressure drops across the pilot metering jet and the regulator jet. Equation (11) applies to a self-setting distributor as well as a preset distributor.

A special case exists for a self-setting distributor when the pilot nozzle pressure is greater than any other nozzle pressure. The pressure drop through the pilot resistance valve must then be included, with the result that the distributor pressure drop is given by the equation

$$\Delta P_c = \Delta P_m + \Delta P_r + \Delta P_s \tag{18}$$

The value of ΔP_s is expressed as

$$\Delta P_s = \left(\frac{JW}{A_{s,max}}\right)^2 \tag{19}$$

The values of ΔP_m and ΔP_r are obtained from equation (9) or (10), and equation (6) or (8), whichever is applicable for the distributor under consideration.

APPENDIX C

APPLICATION OF DISTRIBUTOR SYSTEMS

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The value of the analysis of appendix B may be amplified by considering a typical fuel-distributor application. The following conditions are assumed to be representative of a distributor-application problem.

Flow range	50 to 1
W_{min}	20 lb/hr
W_{max}	1000 lb/hr
J	5.88×10^{-5} $\frac{\text{hr in.}}{\sqrt{\text{lb}}}$ (AN-F-32 fuel)
$\Delta P_{e,min}$	0 lb/sq in.
$\Delta P_{e,max}$	anticipated, $1.5 \times \Delta P_{e,R}$, lb/sq in.

The following design conditions are assumed:

$A_{s,max}$	$A_{v,max}$, 0.025 sq in. (design space limit)
$\Delta P_{b,min}$	minimum controllable pressure drop across fixed-area metering jets, 0.058 lb/sq in (2 in. of AN-F-32 fuel)
ΔP_b	variable-area metering jets, $0.103 + 0.0099\ W$
$\Delta P_{e,R}$	fixed-area spray nozzles, $14.02 \times 10^{-4}\ W^2$ (fixed-area spray nozzles used with distributors PS and PS-VM only)
$\Delta P_{e,R}$	variable-area spray nozzles, $42 + 0.036\ W$
ΔP_r	variable-area regulator jet in present distributor, $1.5 \times \Delta P_{e,R} = 63 + 0.054\ W$. (This assumption will permit regulation of fuel distribution for condition when pilot spray nozzle is operating near zero pressure drop.)
ΔP_r	variable-area regulator jet in self-setting distributor, $5 + 0.02\ W$
$\Delta P_{r,min}$	fixed-area regulator jet in self-setting distributor, 0.1 lb/sq in. (stability limit)

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Distributor Selection

Distributor-pressure drop. - The distributor-pressure drop for the eight distributor arrangements may be computed by substitution of the foregoing conditions in the proper equations presented in the analysis. The results of the calculations are presented in figure 22. The pressure drop for distributors PS and PS-VM using fixed-area nozzles was computed with the pilot nozzle operating at the nominal pressure drop. If the computation were to include the possibility of the pilot nozzle operating near zero pressure drop, the pressure drop across the distributor at the maximum fuel flow would be 2257 pounds per square inch for distributor PS and 2122 pounds per square inch for distributor PS-VM.

A study of figure 22 indicates that distributors with variable-area regulator jets have greatly reduced maximum pressure drops compared to distributors with fixed-area regulator jets. Distributors with variable-area metering jets also have lower maximum pressure drops than the same distributors with fixed-area metering jets.

The preset distributors are sensitive to the pilot spray-nozzle pressure and must be preset to control the anticipated maximum variation in pilot nozzle pressure. The high pressure drops of distributors PS and PS-VM at the maximum fuel-flow rate and the high pressure drops of distributors PS-VR and PS-VR-VM at the minimum fuel-flow rate is due to this sensitivity of the distributor to the pilot nozzle pressure.

Self-setting distributors are not sensitive to the pilot spray-nozzle pressure alone but are sensitive to the highest of all the nozzle pressures. As a result, self-setting distributors have lower distributor-pressure drops than preset distributors.

Selection of a distributor on the basis of pressure drop alone indicates that distributors with both variable-area regulator jet and variable-area metering jets are most desirable for very wide flow ranges.

Accuracy. - Any distributor with a variable-area regulator jet will operate with improved accuracy compared with any distributor with a fixed-area regulator jet. The improvement was demonstrated by the results of studies of the SS-VR distributor (variable-regulator-jet modification of the self-setting-distributor test model). The data also indicated that a distributor with fixed-area metering jets will perform with better accuracy than a distributor with variable-area metering jets. Distributor arrangements PS-VR and SS-VR will perform with the best distribution accuracy.

<ins>Range of spray-nozzle pressures.</ins> - Fuel-distributors PS and PS-VM can be used to feed only fixed-area spray nozzles. The pressure-drop curves for distributors PS and PS-VM shown in figure 22 were computed for the condition at which the pilot spray nozzle is operating at its rated pressure drop. (See appendix B.) If the pilot nozzle pressure should decrease below the rated pressure drop, the distributor will not function and the fuel distribution is governed by the resistances of the various spray nozzles. Thus the range of controllable pilot nozzle pressures for distributors PS and PS-VM is limited. A compromise must therefore be made between a short range of controllable pilot nozzle pressures and an excessive distributor-pressure drop. 1349

Distributors PS-VR and PS-VR-VM have variable-area regulator jets and may be used to feed variable-area spray nozzles. (See appendix B.) The pressure-drop curves for distributors PS-VR and PS-VR-VM in figure 22 were computed for variable-area spray nozzles including the full range of anticipated pilot-nozzle-pressure variation and will distribute fuel equally to all the spray nozzles over the complete range of anticipated spray-nozzle pressures. If a nozzle pressure increased beyond the anticipated maximum nozzle pressure, the fuel flow to that nozzle will decrease and the fuel distribution will be altered. An exception occurs when the pilot spray-nozzle pressure increases above the maximum pressure anticipated. In this case the fuel distribution is undisturbed but the fuel-pressure level at the entrance to the distributor will be increased. Also, if the pilot-nozzle pressure rises exceptionally high, the equalizing valves may not function because a valve area less than the minimum area may be required.

Self-setting distributors will operate over an infinite range of controllable spray-nozzle pressures with one limitation. If an exceptionally large difference should occur between any two nozzle pressures the equalizing valve in the line feeding the lower nozzle pressure may not function because a valve area less than the minimum area may be required. The fuel-pressure level at the inlet to self-setting distributors is a function of the highest spray-nozzle pressure. Either fixed-area or variable-area spray nozzles may be used with this group of distributors. Self-setting distributors should be selected for compensating a wide range of spray-nozzle pressures.

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Selection compromise. - The final selection of a fuel distributor must be a compromise to meet the requirements of a given application. For a 50 to 1 range of fuel-flow rates, an SS-VR distributor is the most desirable distributor. The SS-VR distributor has good accuracy, a wide range of controllable spray-nozzle pressures, and a relatively low maximum-pressure drop. The good performance characteristics of the SS-VR distributor are substantiated by the data presented.

Use of the SS-VR distributor for flow ranges of the order of 100 to 1 may result in excessive maximum pressure drops. In this case distributors PS-VR-VM or SS-VR-VM would have to be used in spite of the probable decrease in accuracy resulting from use of variable-area metering jets. The SS-VR-VM distributor is a relatively complex distributor but retains a wide range of controllable spray-nozzle pressures and lower distributor pressure drops over the full range of fuel flows. The PS-VR-VM distributor is less complex but has a narrower range of controllable spray-nozzle pressures and higher distributor pressure drops over the full range of fuel-flow rates. The choice will depend on the possible variation of spray-nozzle pressures and the pressure potential available for distributing the fuel.

Distributor Components

Areas of variable components. - The areas and area ranges required for variable components of each of the eight distributor arrangements may be computed from the relations presented in the analysis of appendix B and the conditions of the typical problem. The results of the computations are shown in the following table:

Distributor	$A_{v,min}$	$A_{v,max}$	N_v	N_s	N_r	N_b
PS	0.001109	0.025	22.5	---	----	---
PS-VR	.0001038	.025	241.0	---	37.0	---
PS-VM	.001109	.025	22.5	---	----	8.7
PS-VR-VM	.0001038	.025	241.0	---	37.0	8.7
SS	.0001466	.00372	25.4	171	----	---
SS-VR	.000141	.01175	83.3	171	23.2	---
SS-VM	.0001466	.00372	25.4	171	----	8.7
SS-VR-VM	.000141	.01175	83.3	171	23.2	8.7

Equalizing valve. - Equalizing-valve-area ranges required for fuel distributors shown in the preceding table indicate a valve-design problem. The valve must be precisely balanced to regulate accurately the downstream pressure of the metering jets. The balancing problem precludes use of a complete shutoff valve. A piston-type valve can be accurately balanced but close fits of the order of 0.0001-inch diametral clearance would be required to meet the minimum-area requirements.

A further requirement of the valve is that it must be stable over the full range of areas. A useful guide to producing a stable valve is a logarithmic relation between area and valve travel. The relation for computing the travel required at various fuel-flow rates is expressed as follows:

$$B = \frac{B_{max} \log \frac{W}{W_{min}}}{\log \frac{W_{max}}{W_{min}}} \tag{20}$$

where

B valve travel, in.

B_{max} maximum design-valve travel, in.

W fuel-flow rate, lb/hr

The area required for each fuel-flow rate W used in equation (20) may be computed from the following expression:

$$A = \frac{JW}{\sqrt{\Delta P}} \tag{21}$$

Areas obtained from equation (21) plotted as a function of valve travel obtained from equation (20) result in a logarithmic curve. For the wide equalizing-valve-area ranges required, an area change on the logarithmic curve is difficult to obtain.

The size of the diaphragm operating the equalizing valve is another factor to consider. A large diaphragm will regulate a desired pressure with greater accuracy than a small diaphragm. A small metering-jet pressure drop can therefore be regulated by a large diaphragm with the same accuracy as a larger metering-jet

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pressure drop regulated by a smaller diaphragm. The choice depends on the space available and the pressure drop available for metering fuel. It may also be desirable to minimize the weight of the moving valve parts to minimize inertia effects.

Variable length of flow path. - A method for controlling small flow rates at high pressure drops as applied to an equalizing valve is shown in figure 23. The valve consists of a spool-type piston fitted in a sleeve with a predetermined clearance. The valve is balanced by admitting fuel under pressure from the valve inlet to the bottom of the lower spool through the balance passage. For large fuel flows and low pressure drops, the piston operates in such a position that the open area required is obtained by the exposed length of slots cut in the upper spool of the piston. For low fuel flows and high pressure drops the piston is allowed to travel into the sleeve beyond the end of the slots in the piston, such as the position shown in figure 23. Fuel flow occurs as leakage through the clearance on both ends of the spool. The flow through the leakage path is a function of pressure drop, radial clearance, length of path, diameter of piston, and the fluid properties. The relation for fluid flow through thin annular clearances is given in reference 6. For a given valve and a given fluid, all quantities are constant except the pressure drop, the length of path, and the flow rate. For a constant pressure drop, the flow increases in a hyperbolic relation with decrease in the length of flow path. The hyperbolic relation can be made to closely approximate a logarithmic relation. A valve incorporating a variable length of flow path is inherently stable when the variable length of path is properly matched to the variable-area portion of the valve travel.

The theoretical relations for flow through thin annular clearances may not be valid for short lengths of flow path where the flow entrance and exit effects become appreciable. Turbulent flow may exist and the exact flow relation will vary with the valve design. The relations, however, are sufficiently accurate for approximating a valve design.

The variable length of flow path allows use of reasonable clearances between the piston and sleeve. For example, control of a rate of flow of 10 pounds per hour at a pressure drop of 100 pounds per square inch would require an effective area of 0.0000588 square inch. The diametral clearance for a 0.25-inch-diameter piston to obtain 0.0000588 square inch as a minimum area would be 0.0001498 inch. Use of a length of flow path equal to 0.125 inch for the same conditions results in a diametral clearance of 0.001621 inch, which is more than ten times the clearance required for the variable-area valve.

<u>Variable-area regulator jet.</u> - The principle of variable length of flow path is useful in design of a variable-area regulator jet. The variable length of path may be used to meter the flow at low flow rates and a variable area may be used at the high flow rates.

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<u>Pilot resistance valve.</u> - The pilot resistance-valve construction may be similar to the equalizing-valve construction. The maximum area is as large as space permits to reduce the pilot-valve pressure drop to a minimum in the event the pilot spray nozzle has the highest resistance.

<u>Variable-area metering jets.</u> - The maximum area of round variable metering jets is determined by the maximum desired pressure drop at the maximum fuel-flow rate. The minimum area is as large as possible consistent with the minimum pressure drop controllable by the equalizing valves at the minimum-flow rate. The minimum area is as large as possible to minimize the effect of hole-size variations between jets.

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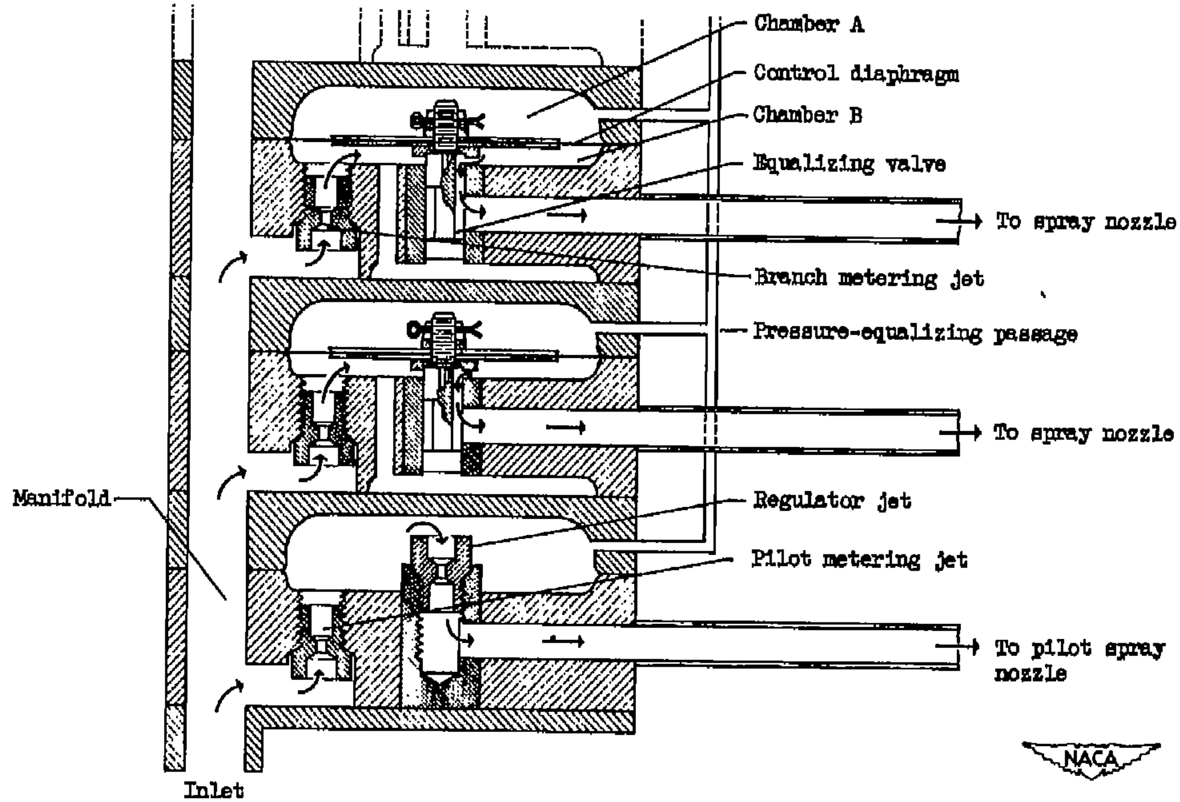

Figure 1. - Schematic diagram of basic fuel distributor.

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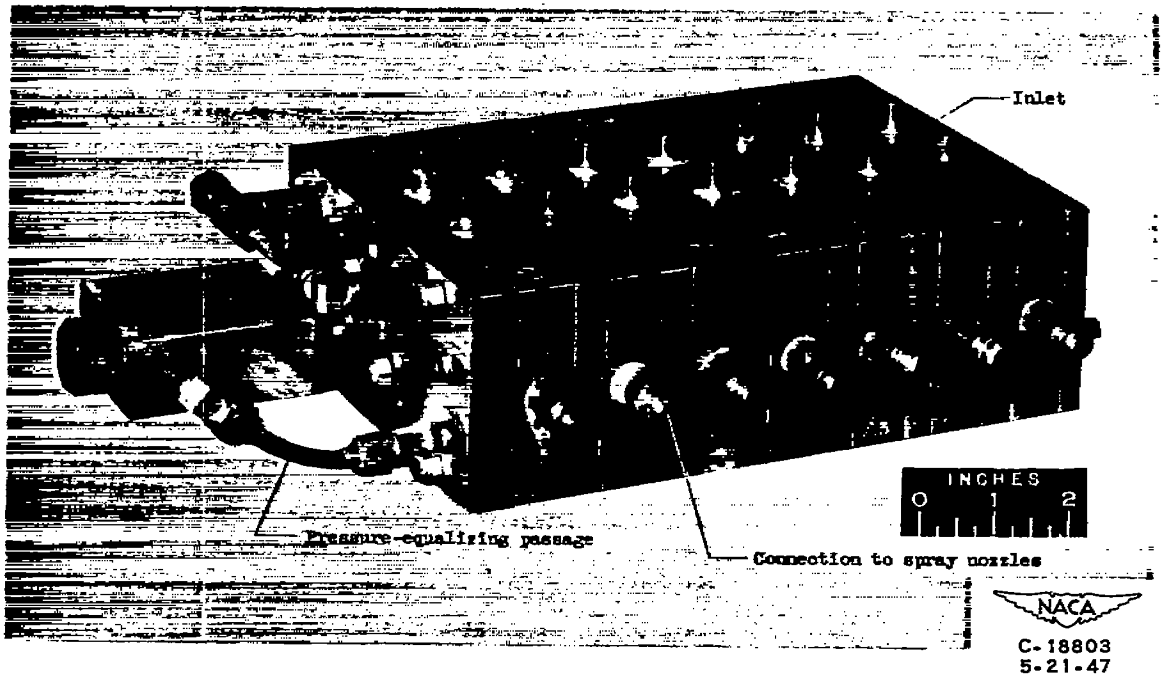
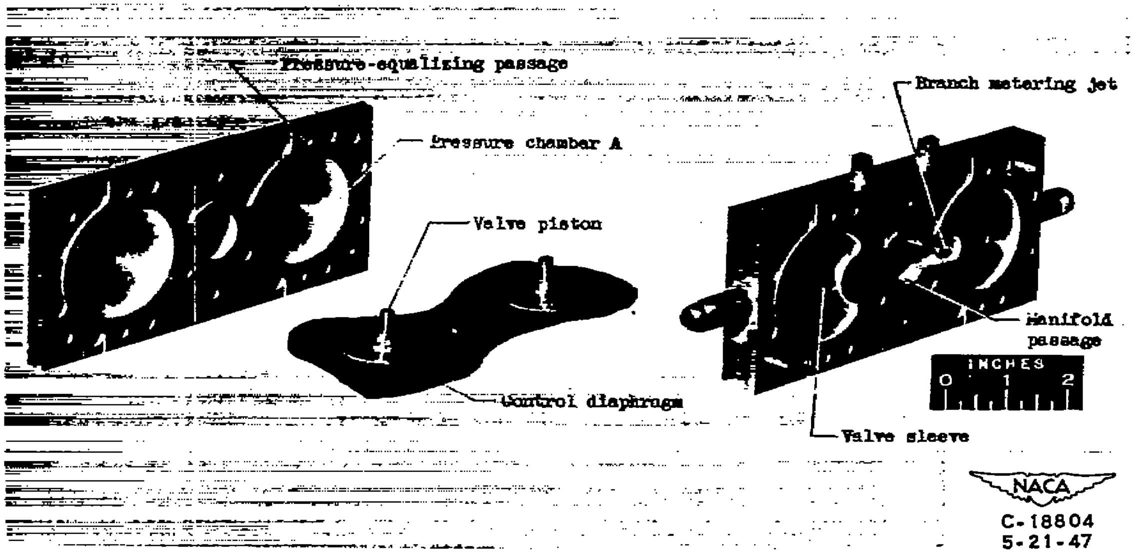


(a) Assembled distributor.



(b) Disassembled section of a basic distributor for feeding fuel to two spray nozzles.

Figure 2. - Basic fuel distributor for feeding 14 spray nozzles.

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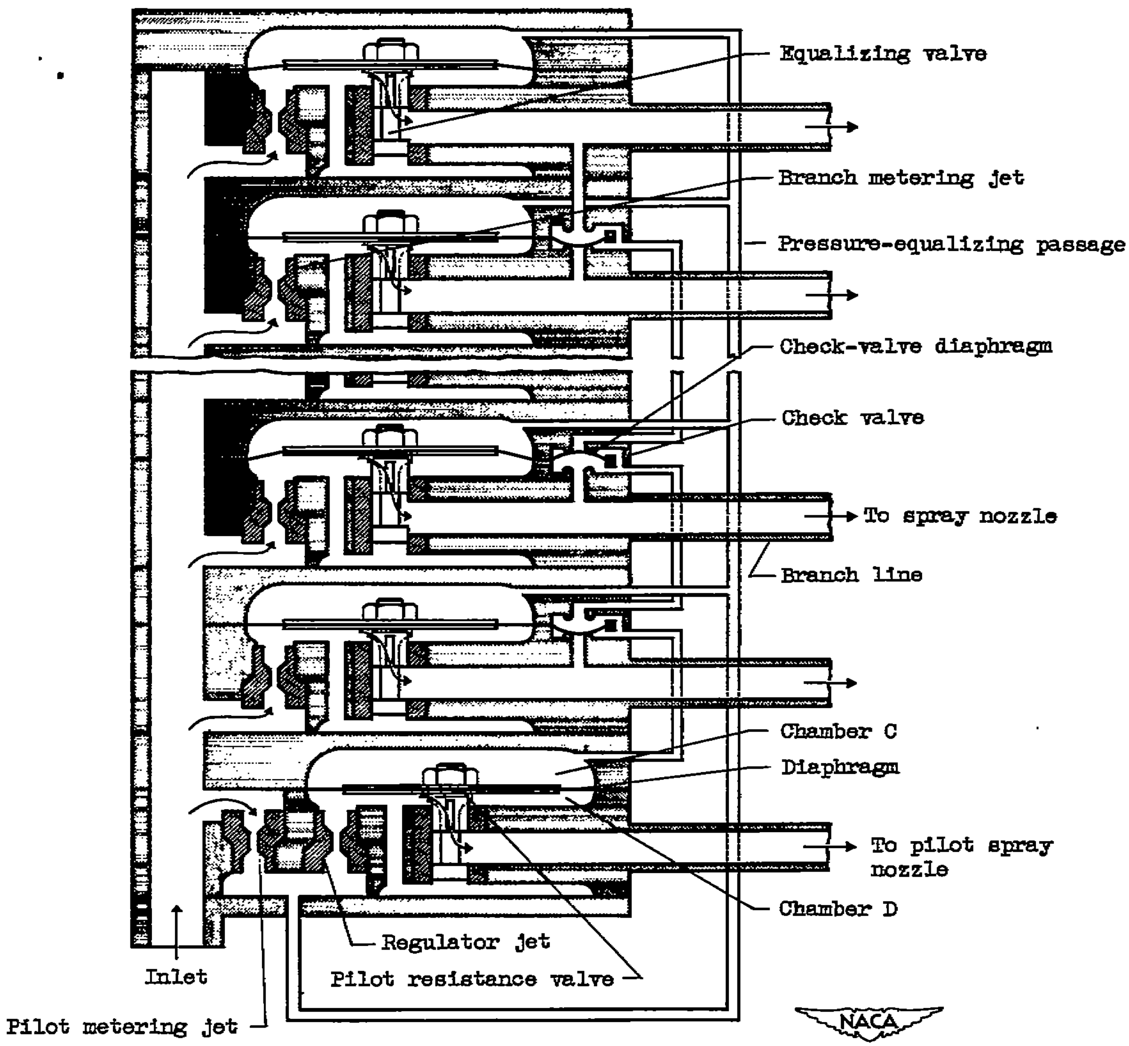

Figure 3. - Schematic diagram of self-setting fuel distributor.

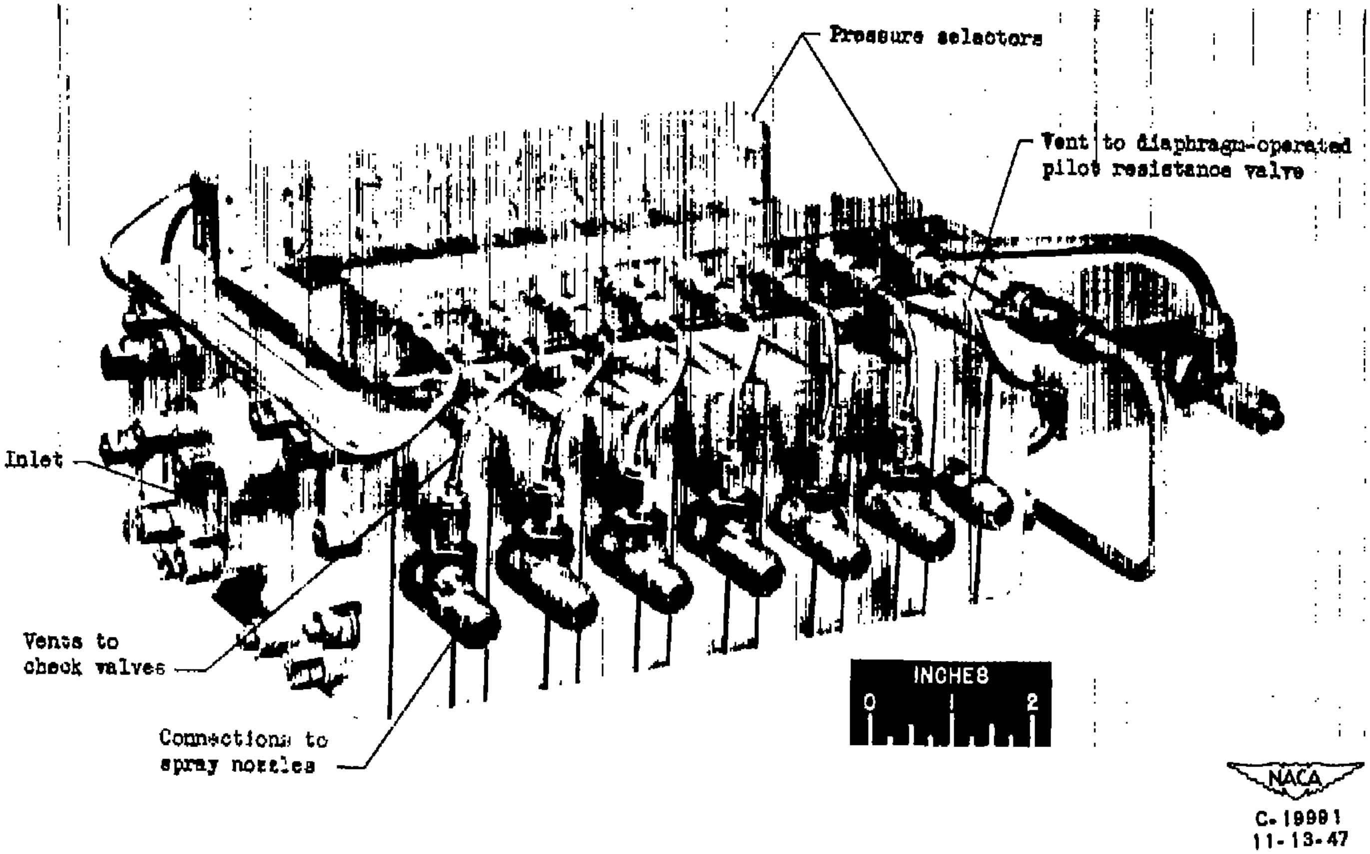

Figure 4. - Self-setting fuel distributor for feeding 14 spray nozzles.

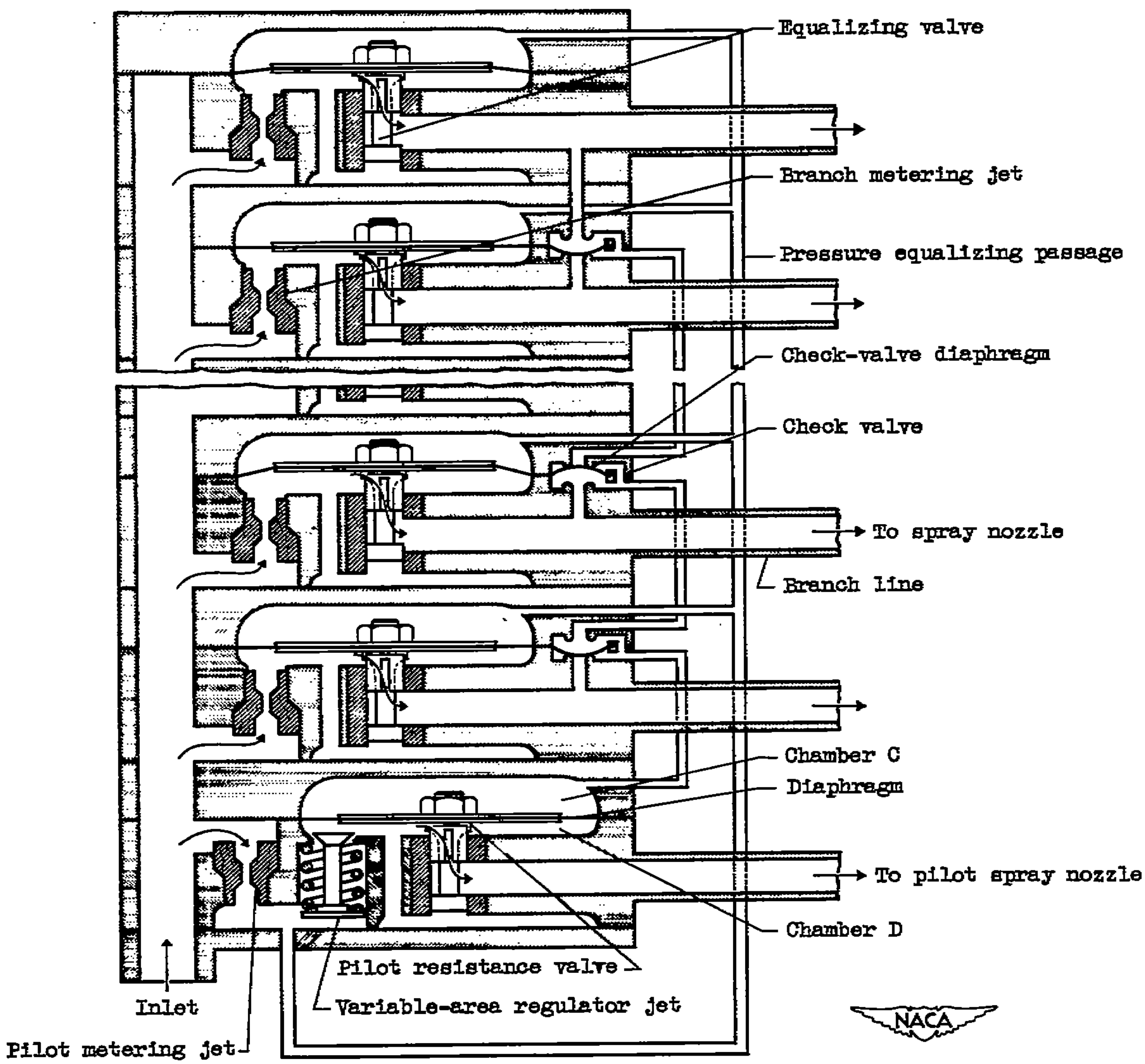

Figure 5. - Schematic diagram of self-setting fuel distributor with variable-area regulator jet.

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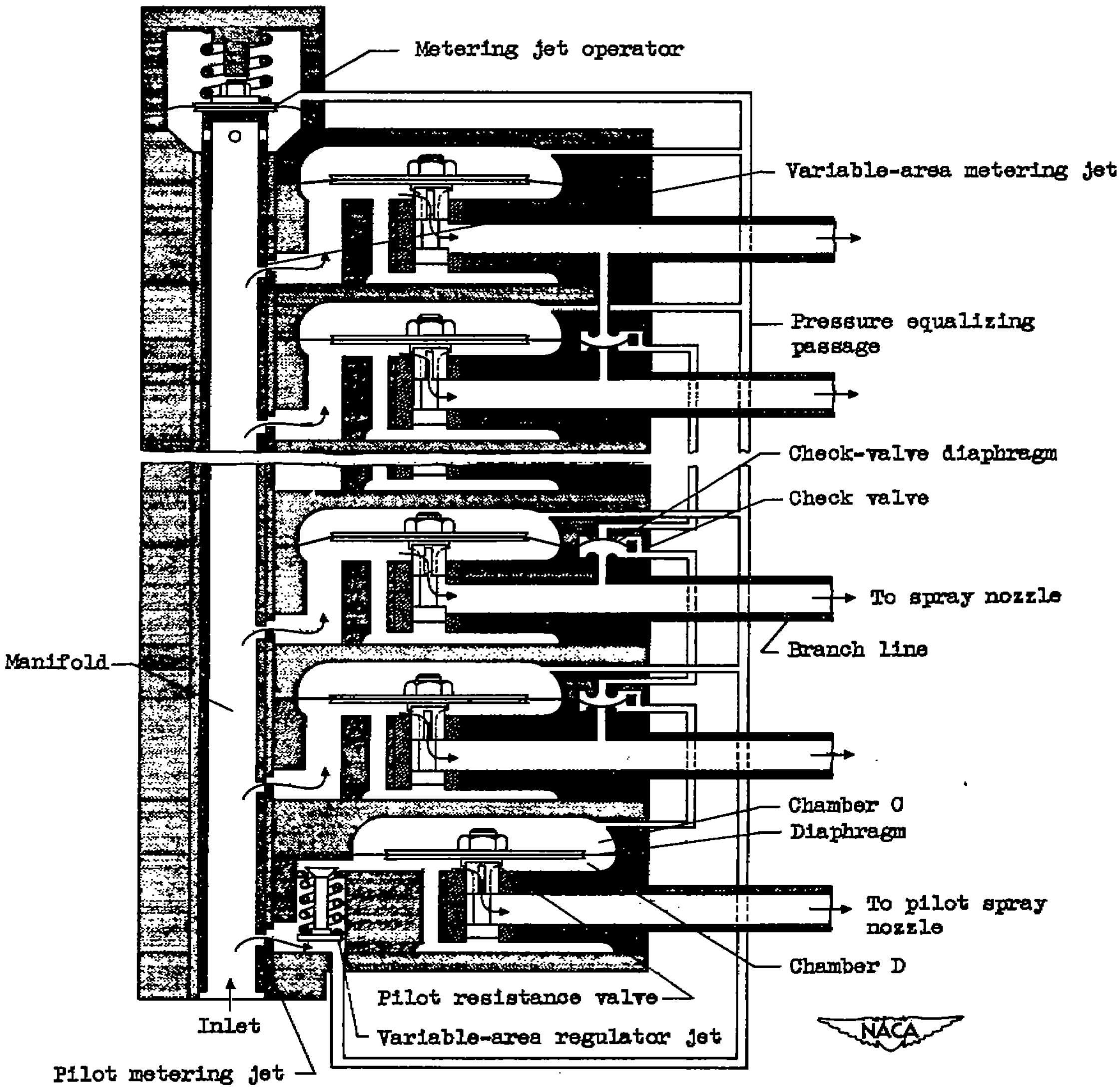

Figure 6. - Schematic diagram of a self-setting fuel distributor with variable-area metering jets and variable-area regulator jet.

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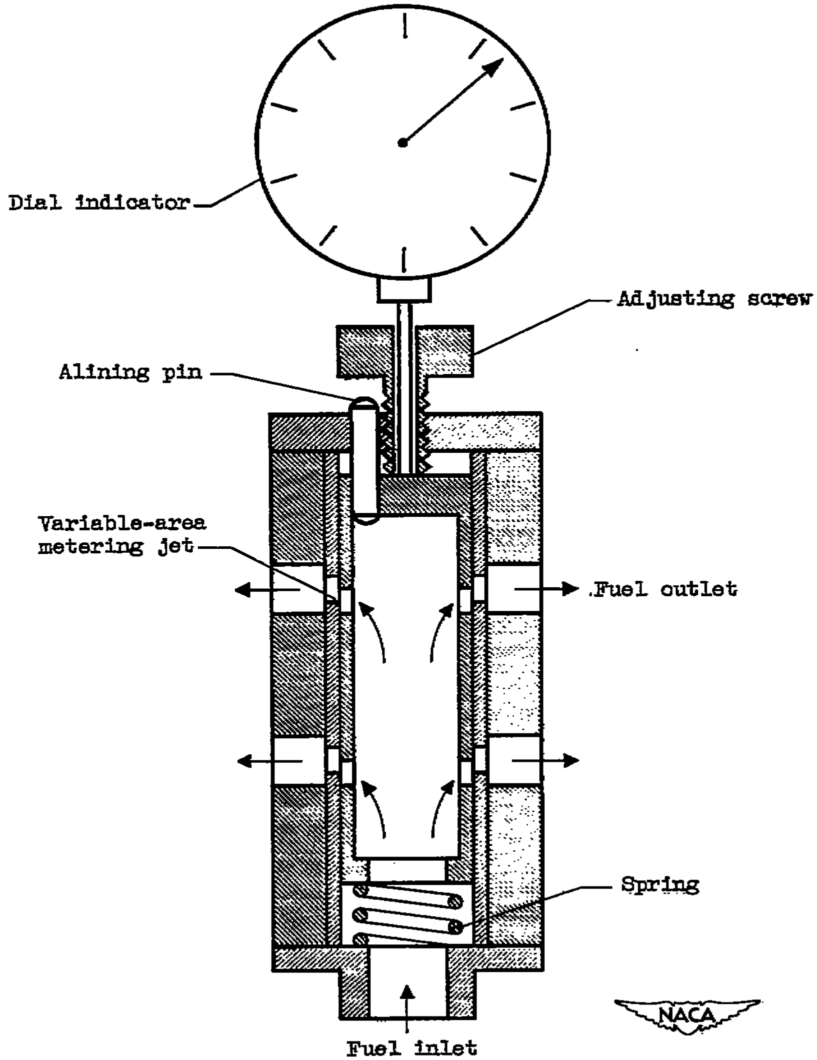

Figure 7. - Schematic diagram of variable-area metering-jet unit used for bench runs.

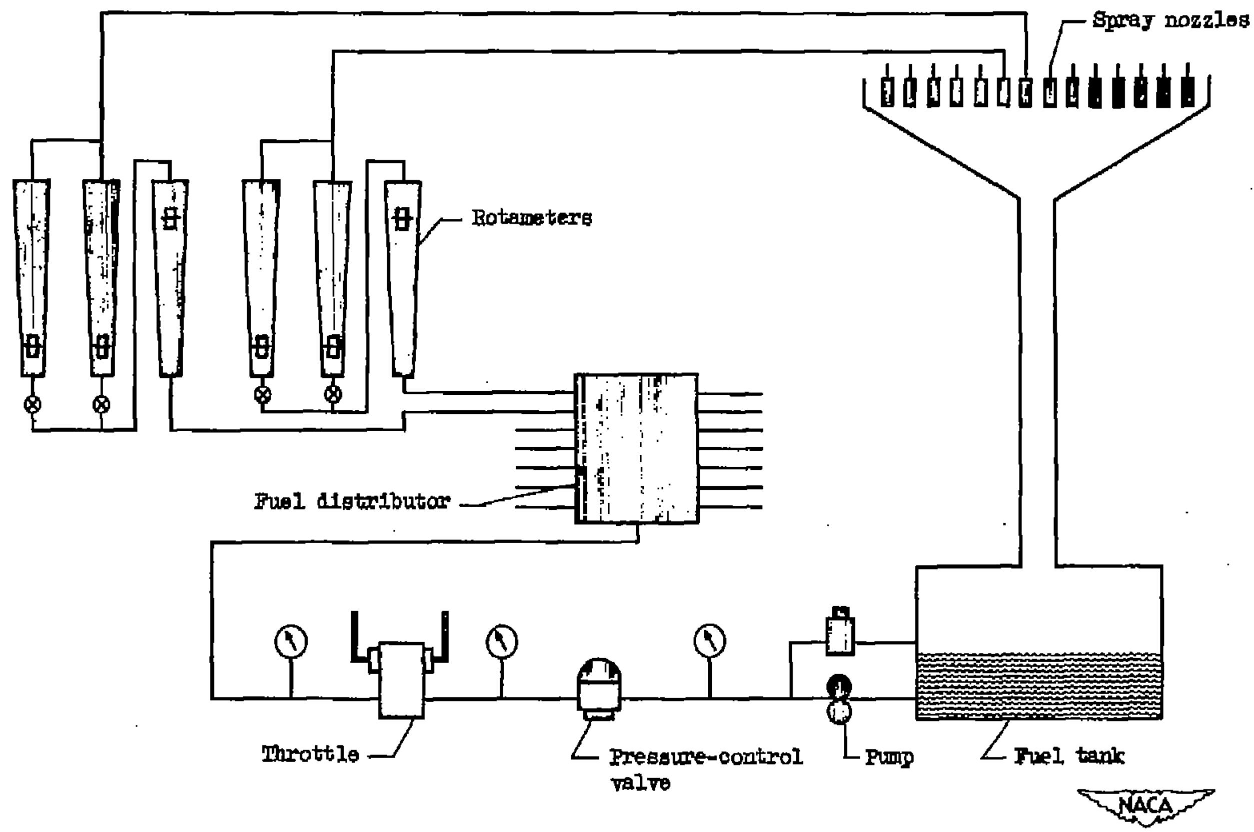

Figure 8. - Schematic diagram of bench apparatus used in fuel-distributor studies.

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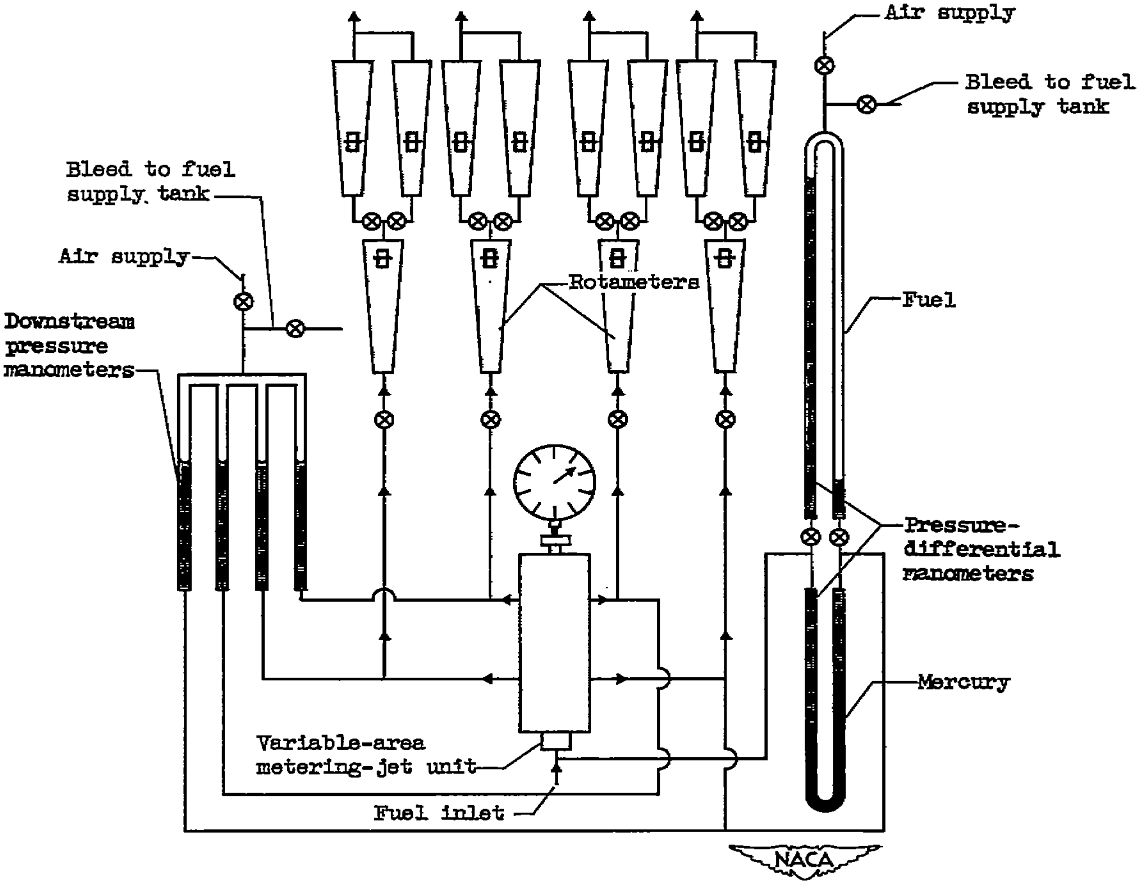

Figure 9.- Schematic diagram of bench apparatus used in studies of variable-area metering jets.

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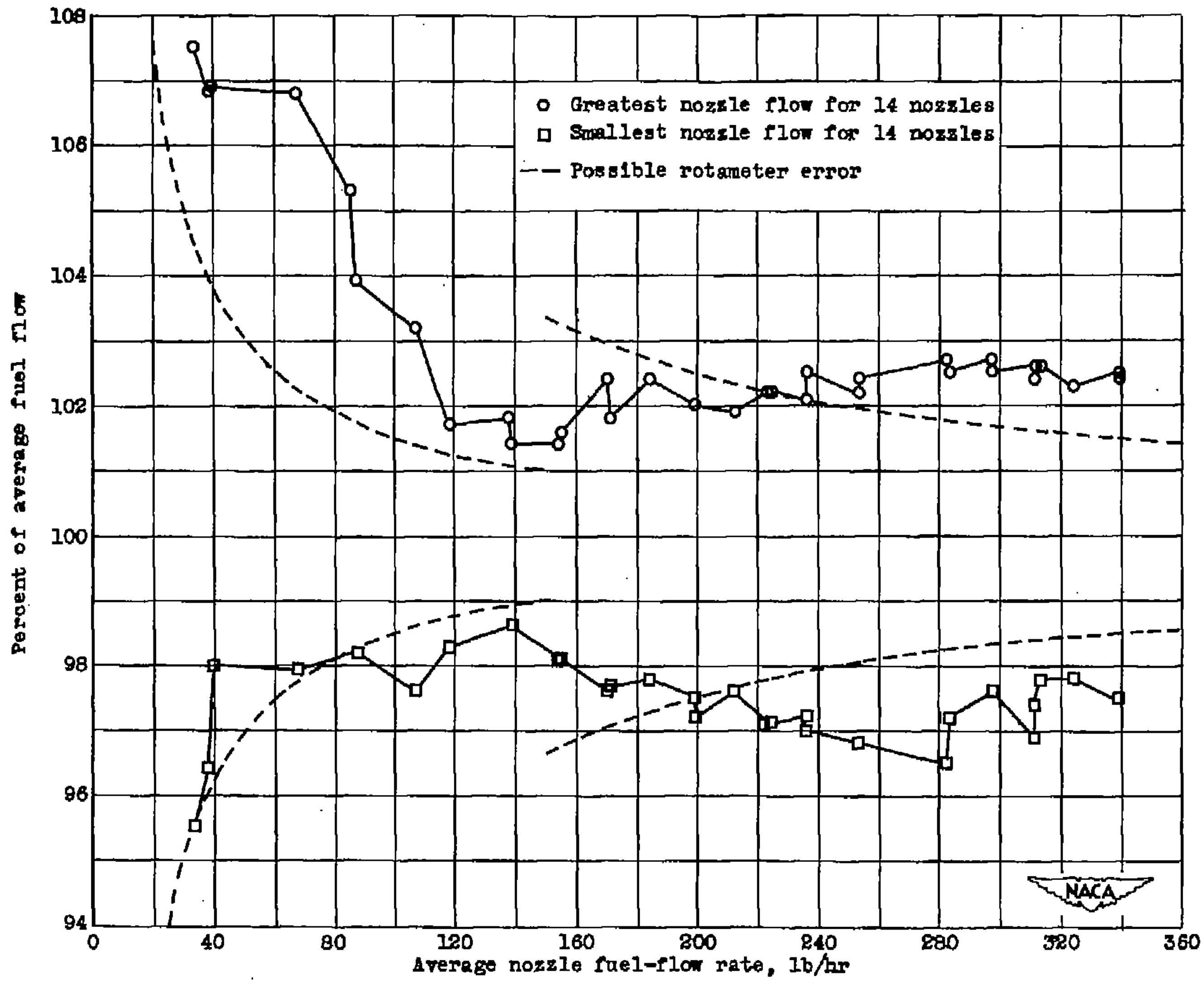

Figure 10. – Distribution accuracy of basic fuel distributor feeding 14 nozzles.

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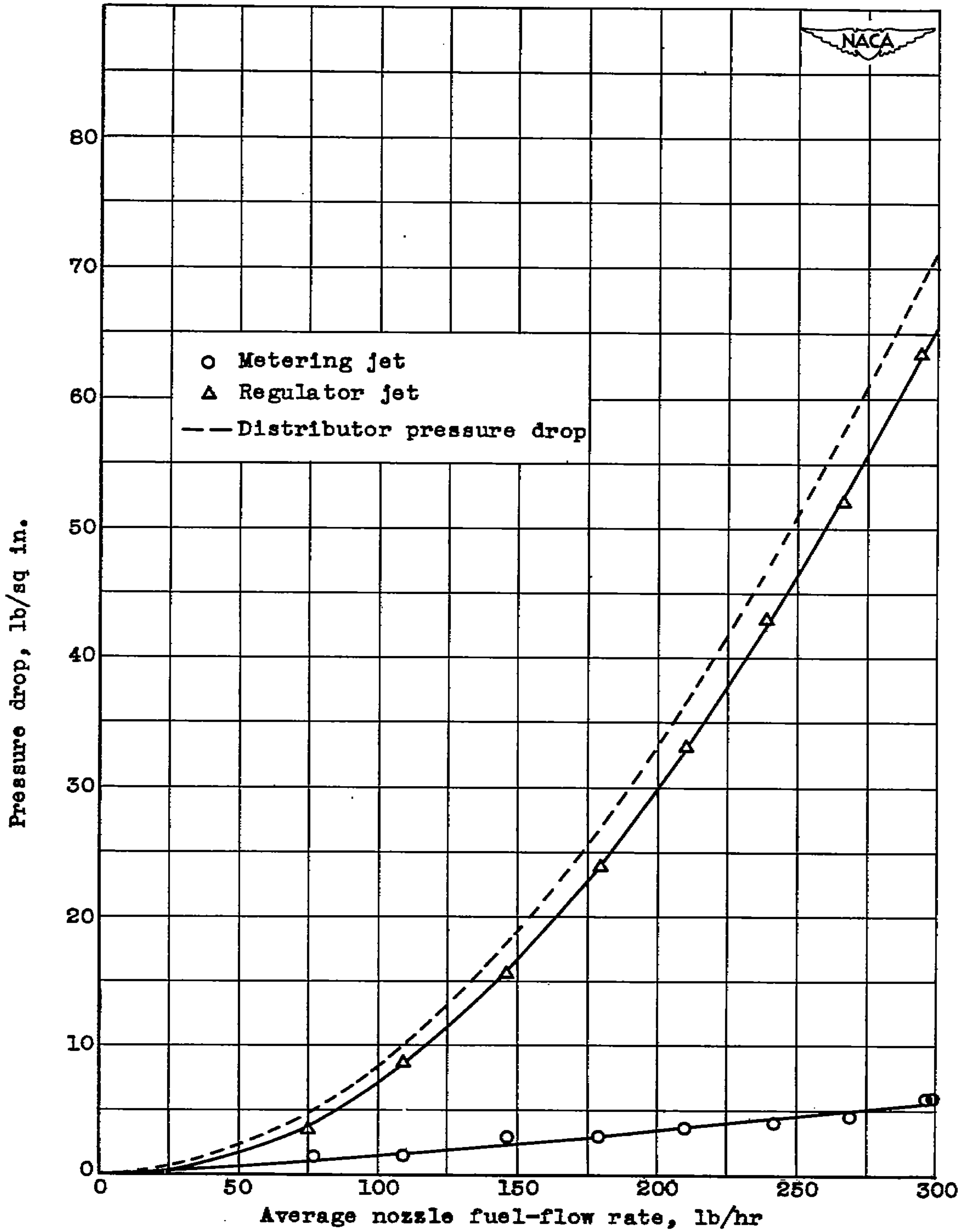

Figure 11. - Variation of pressure drop with fuel-spray nozzle fuel-flow rate for basic fuel distributor.

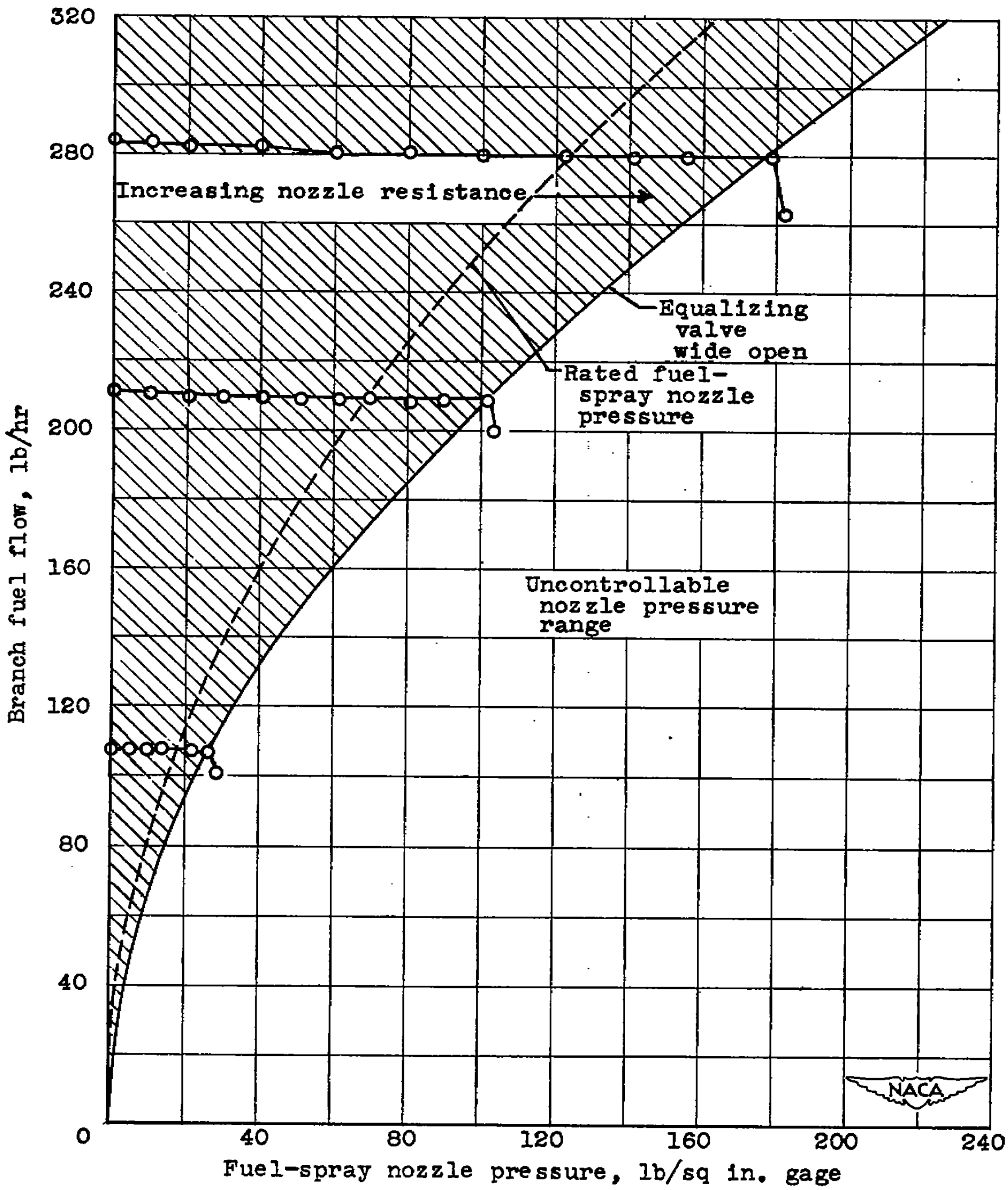

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Figure 12. - Range of controllable fuel-spray nozzle pressures for basic fuel distributor. Shaded area indicates range of controllable nozzle pressures.

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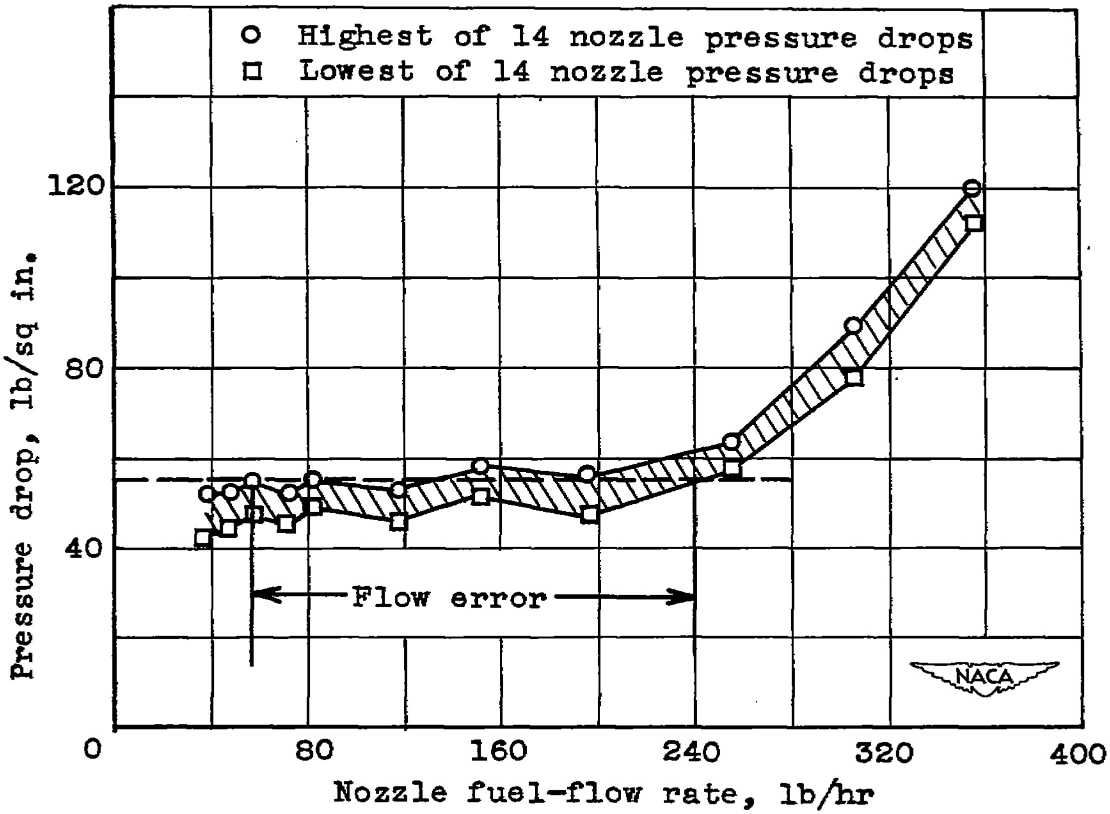


Figure 13. - Calibration spread of variable-area fuel-spray nozzles used in bench runs of self-setting fuel distributor.

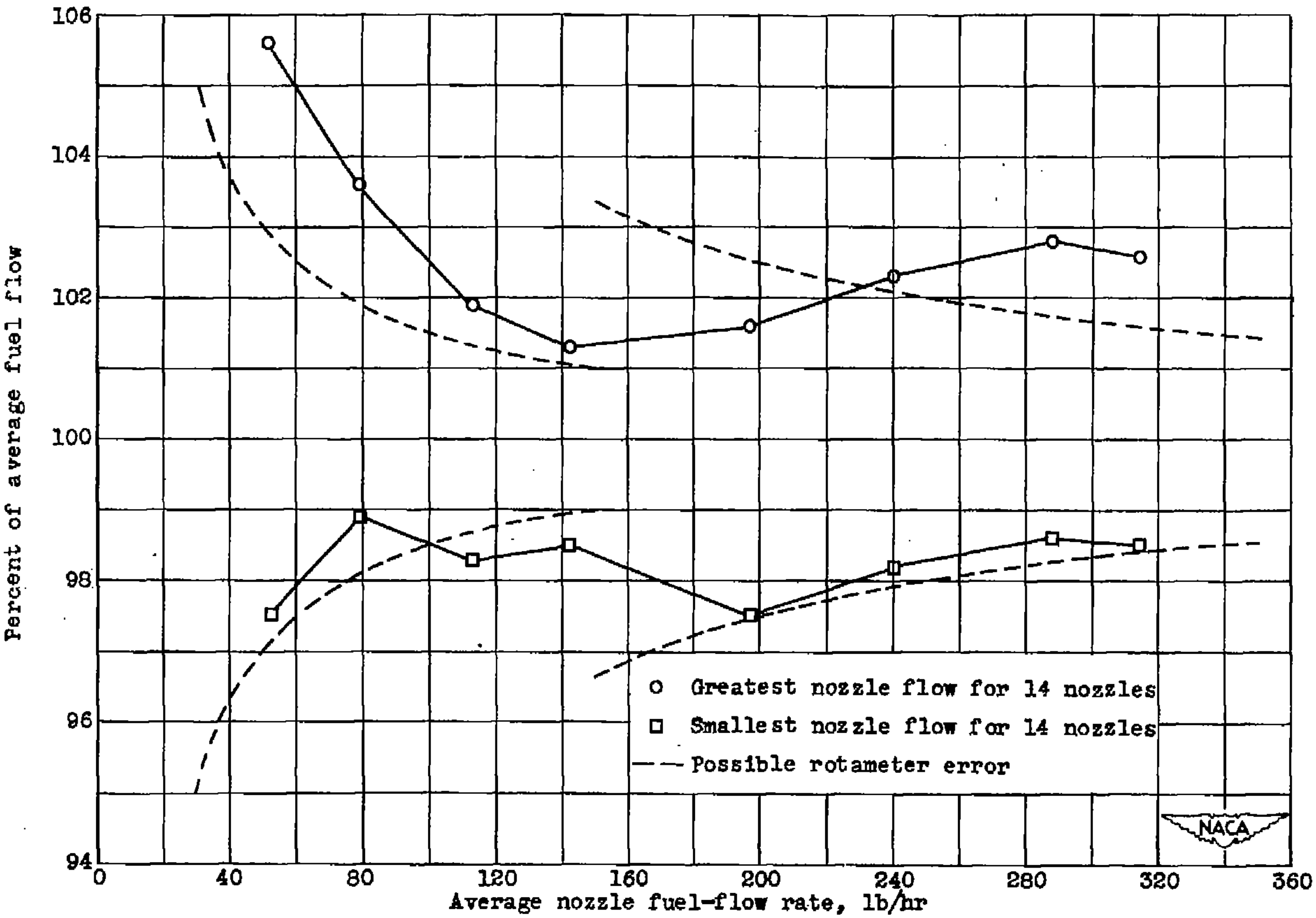


Figure 14. - Distribution accuracy of self-setting fuel distributor feeding 14 nozzles.

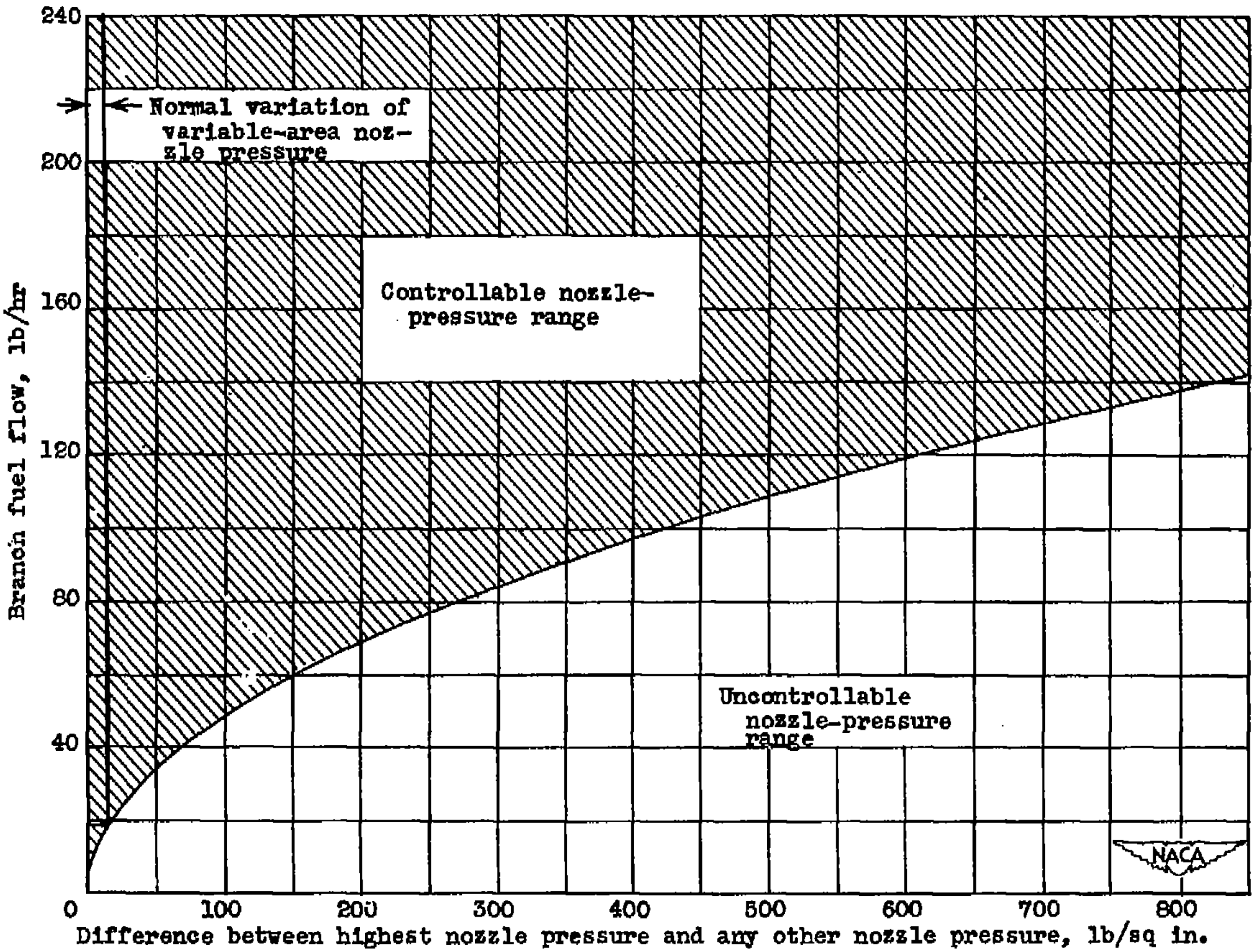


Figure 15. - Range of controllable spray nozzle pressures for self-setting fuel distributor.

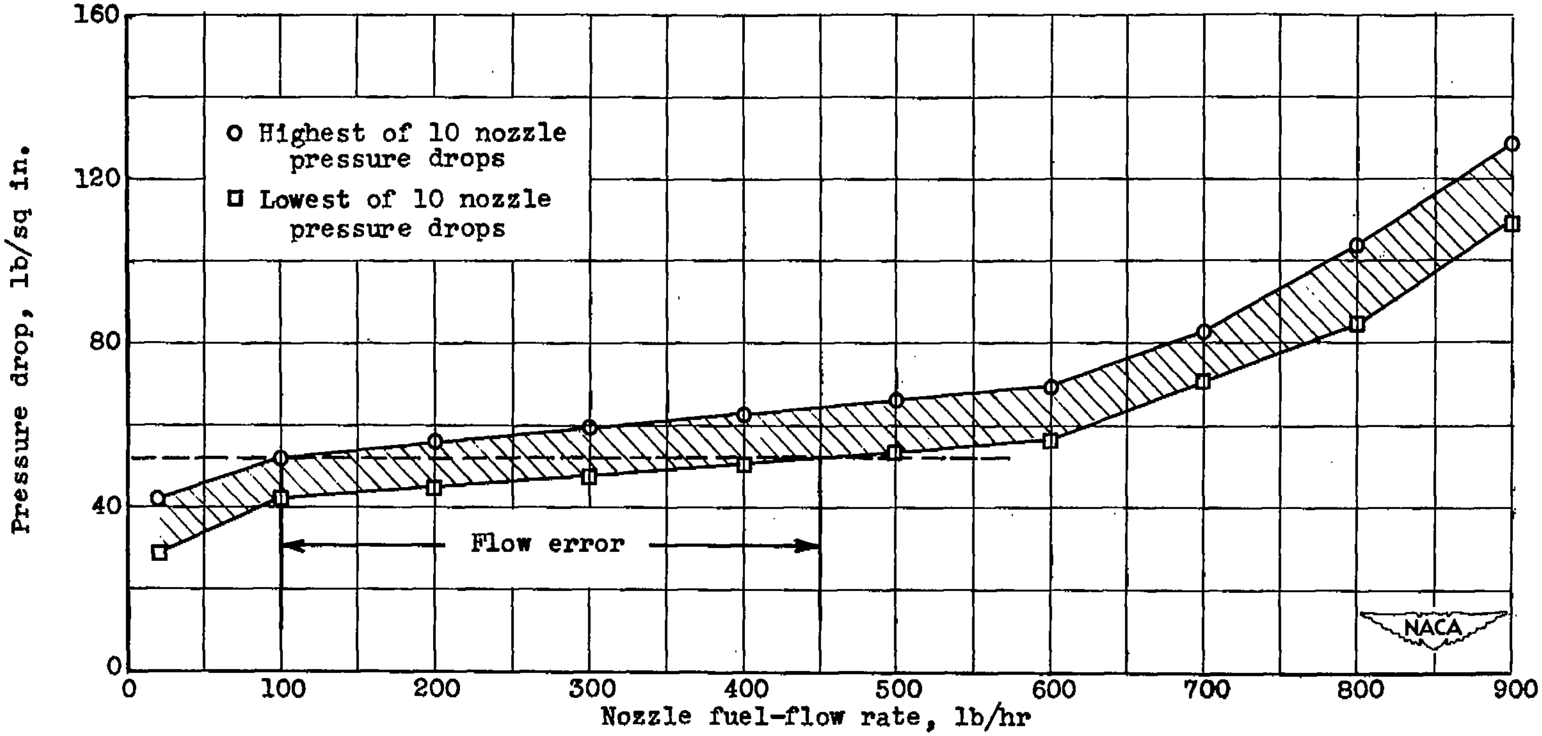


Figure 16. - Calibration spread of variable-area fuel-spray nozzles used in bench investigation of self-setting fuel distributor with variable-area regulator jet.

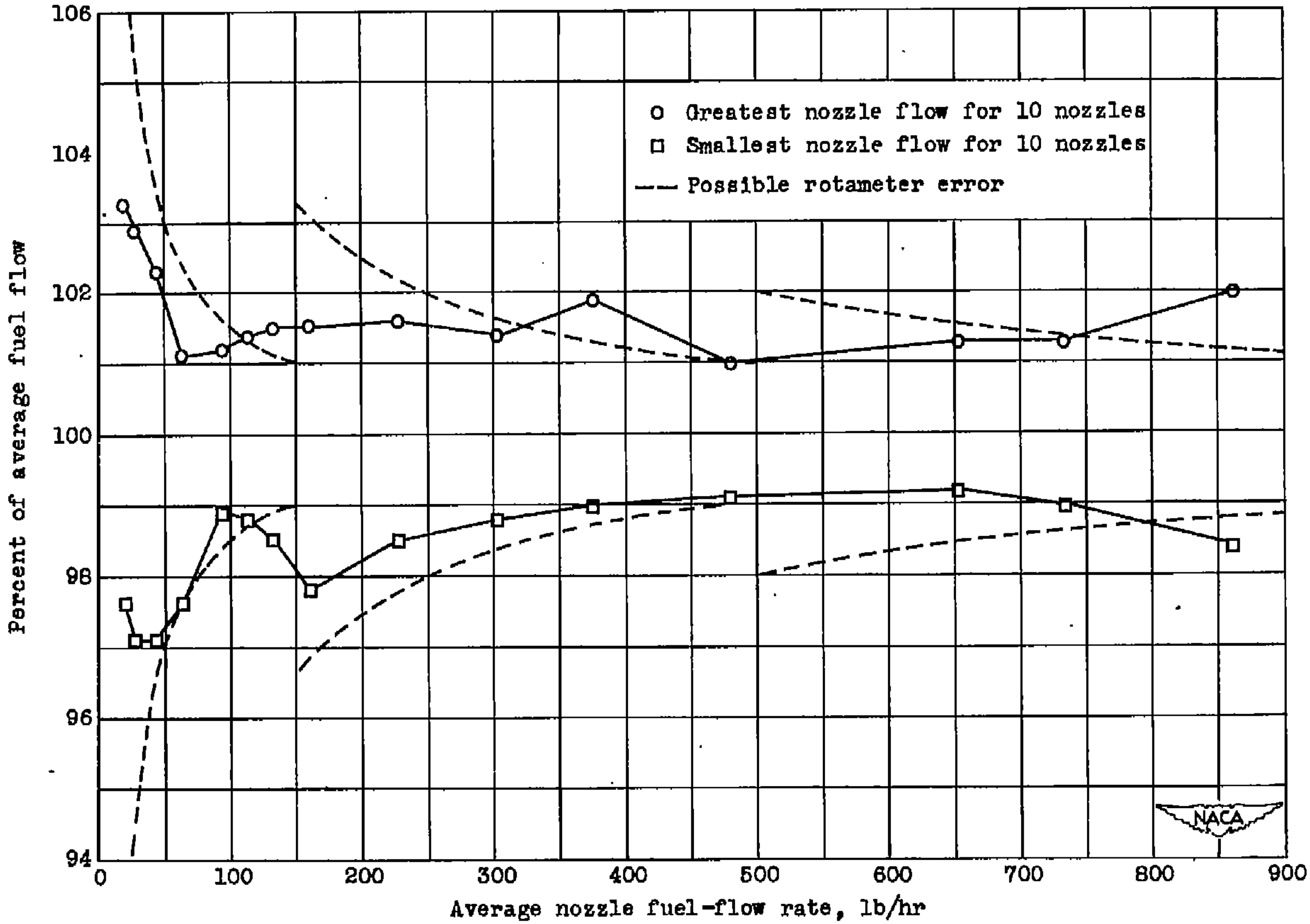


Figure 17. - Distribution accuracy of self-setting fuel distributor with variable-area regulator jet feeding 10 nozzles.

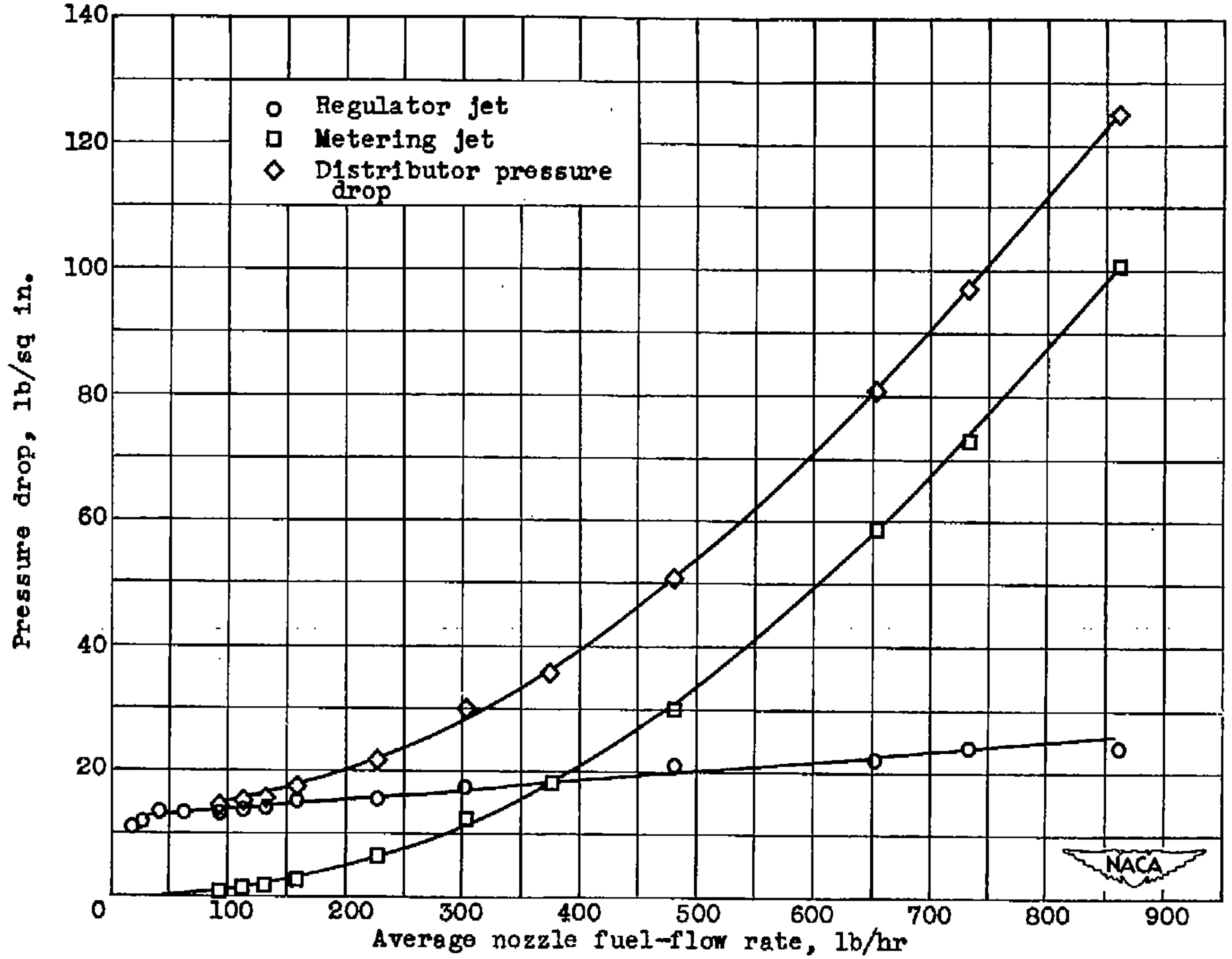


Figure 18. - Variation of component and distributor pressure drops with fuel-spray nozzle fuel-flow rate for self-setting fuel distributor with variable-area regulator jet.

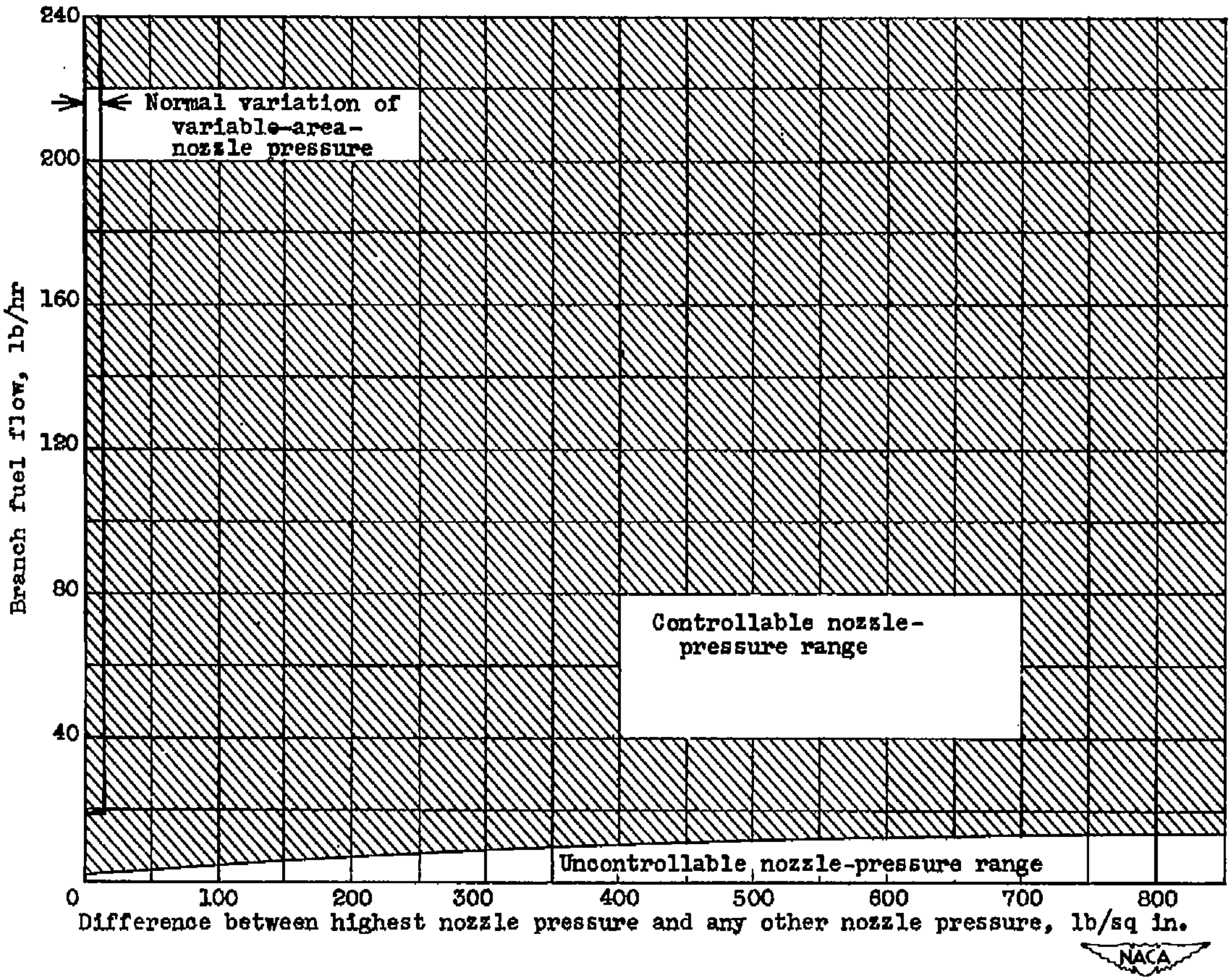


Figure 19. - Range of controllable spray nozzle pressures for self-setting fuel distributor with variable-area regulator jet.

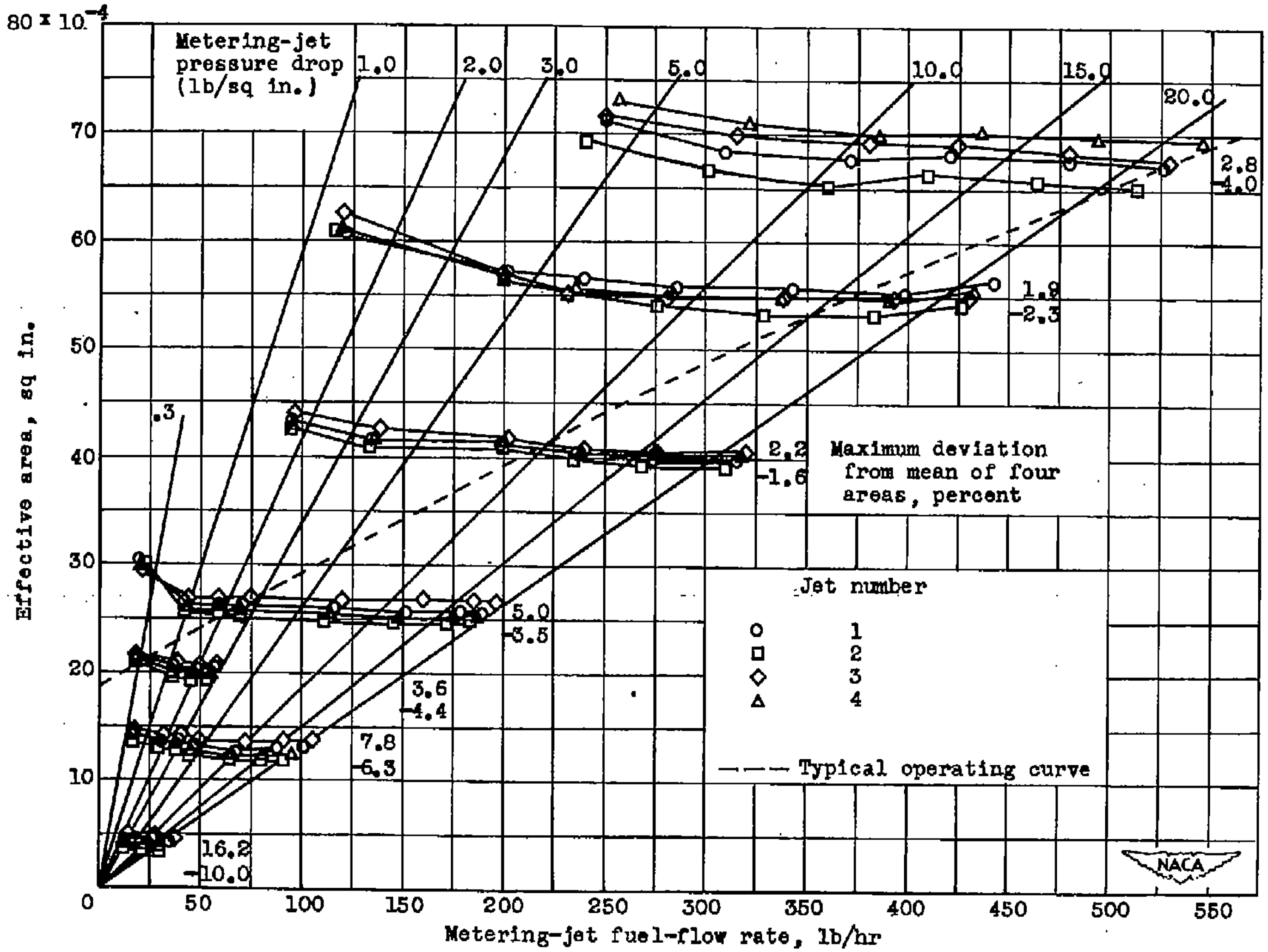
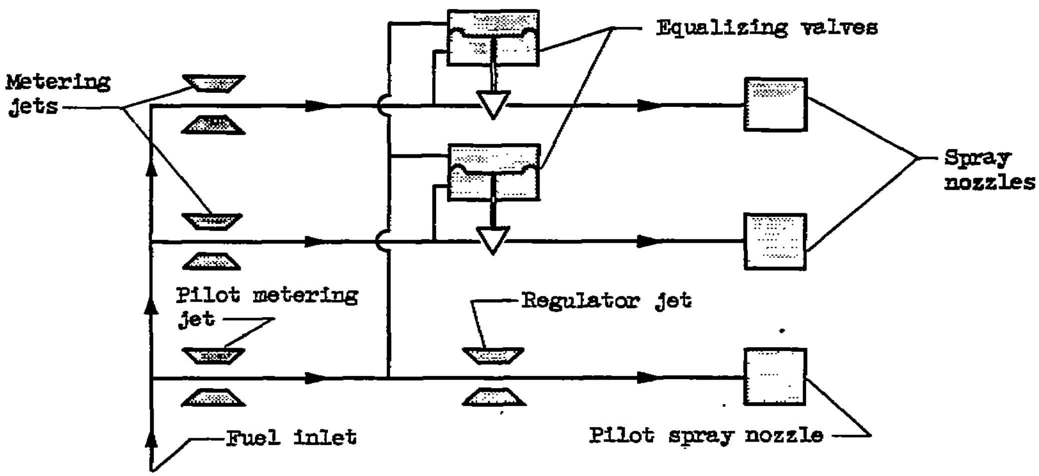
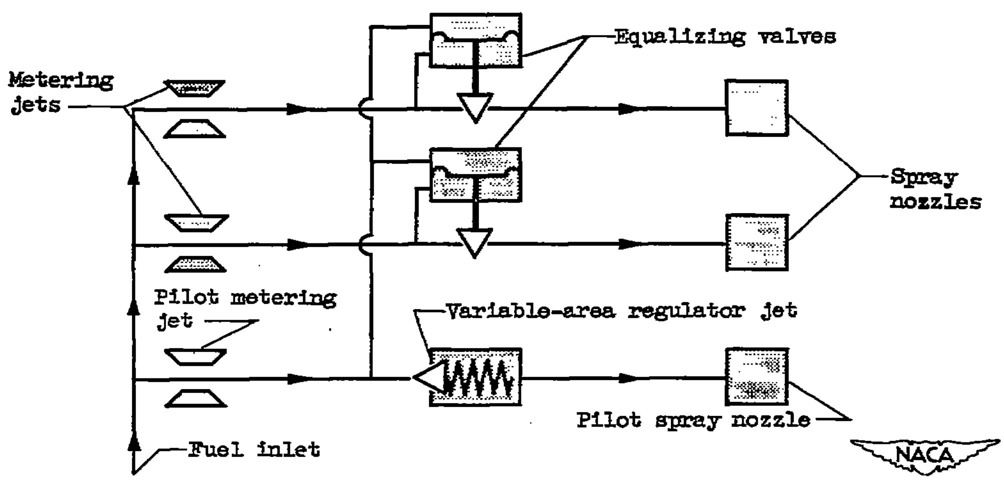


Figure 20. - Bench calibration of variable-area metering-jet unit containing four jets. Calculated typical operating curve superimposed.

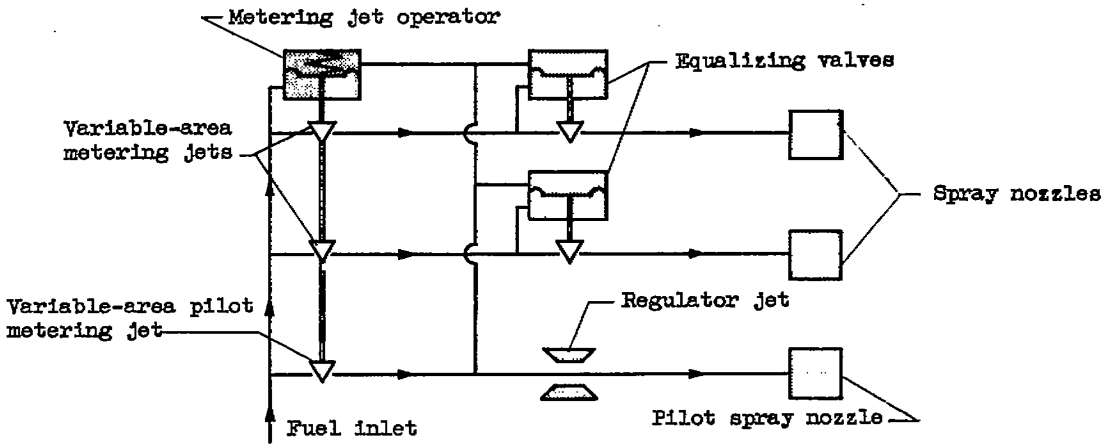


(a) Preset with fixed-area jets (PS).

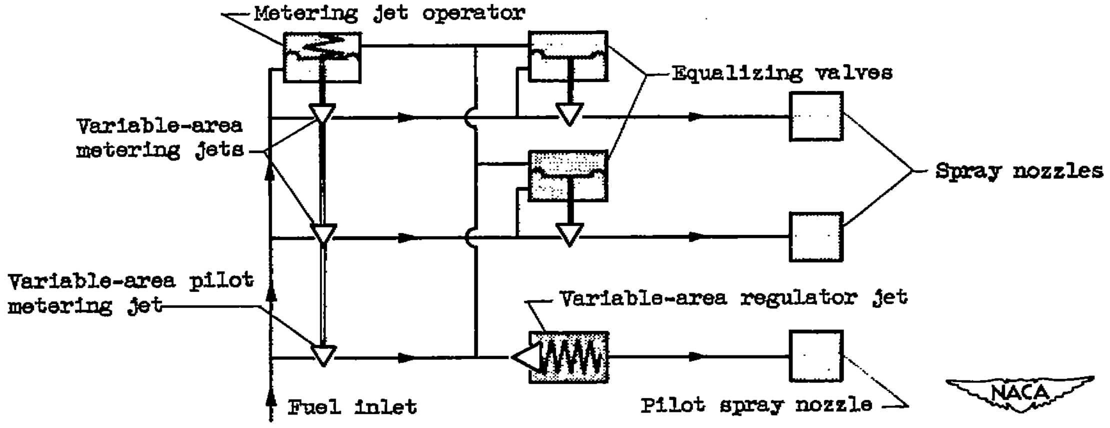


(b) Preset with variable regulator jet (PS-VR).

Figure 21. - Line drawings of eight possible fuel-distributor arrangements.

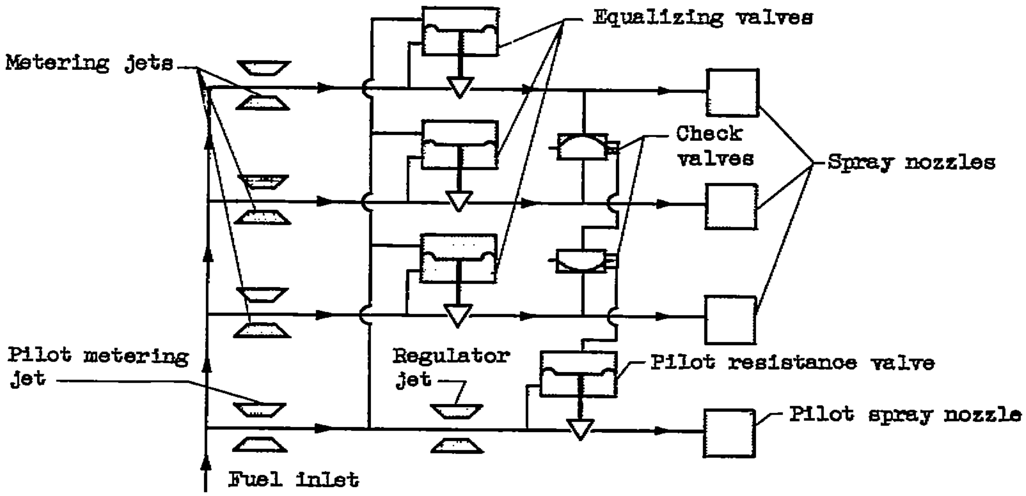


(c) Preset with variable-area metering jets (PS-VM).

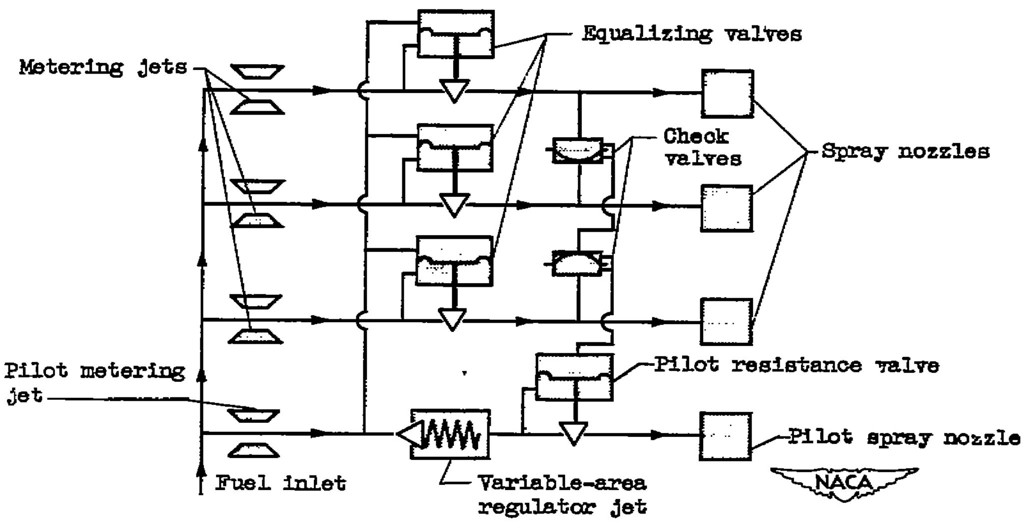


(d) Preset with variable-area regulator and metering jets (PS-VR-VM).

Figure 21. - Continued. Line drawings of eight possible fuel-distributor arrangements.

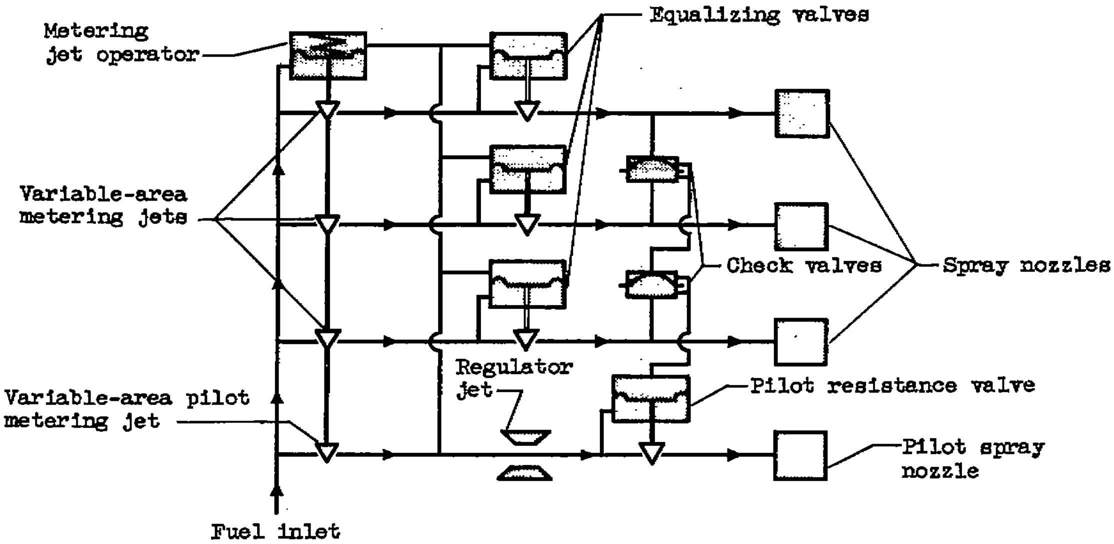


(e) Self-setting with fixed-area jets (SS).

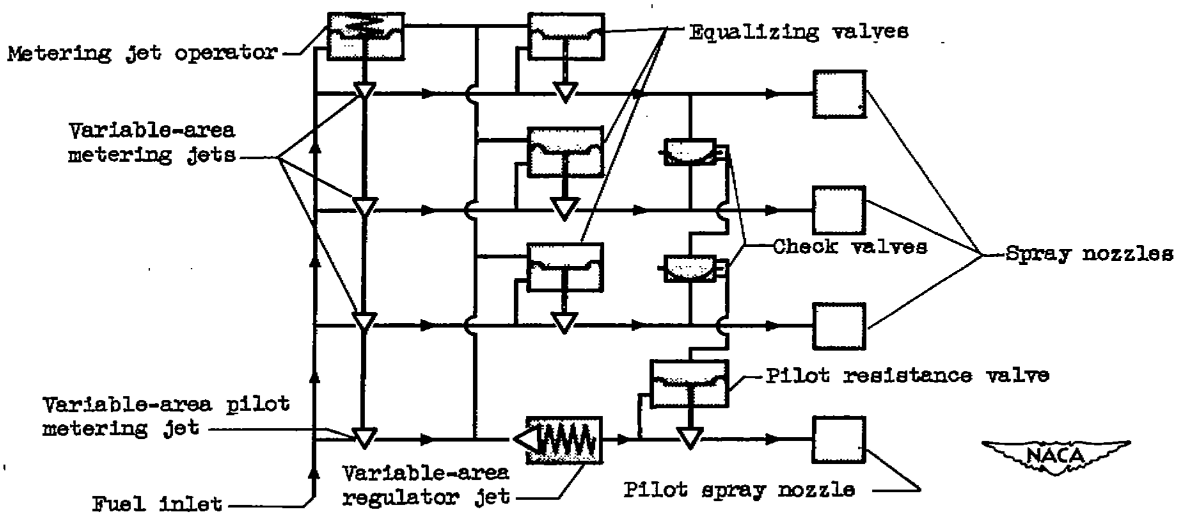


(f) Self-setting with variable-area regulator jet (SS-VR).

Figure 21. - Continued. Line drawings of eight possible fuel-distributor arrangements.



(g) Self-setting with variable-area metering jets (SS-VM).



(h) Self-setting with variable-area regulator and metering jets. (SS-VR-VM).

Figure 21. - Concluded. Line drawings of eight possible fuel-distributor arrangements.

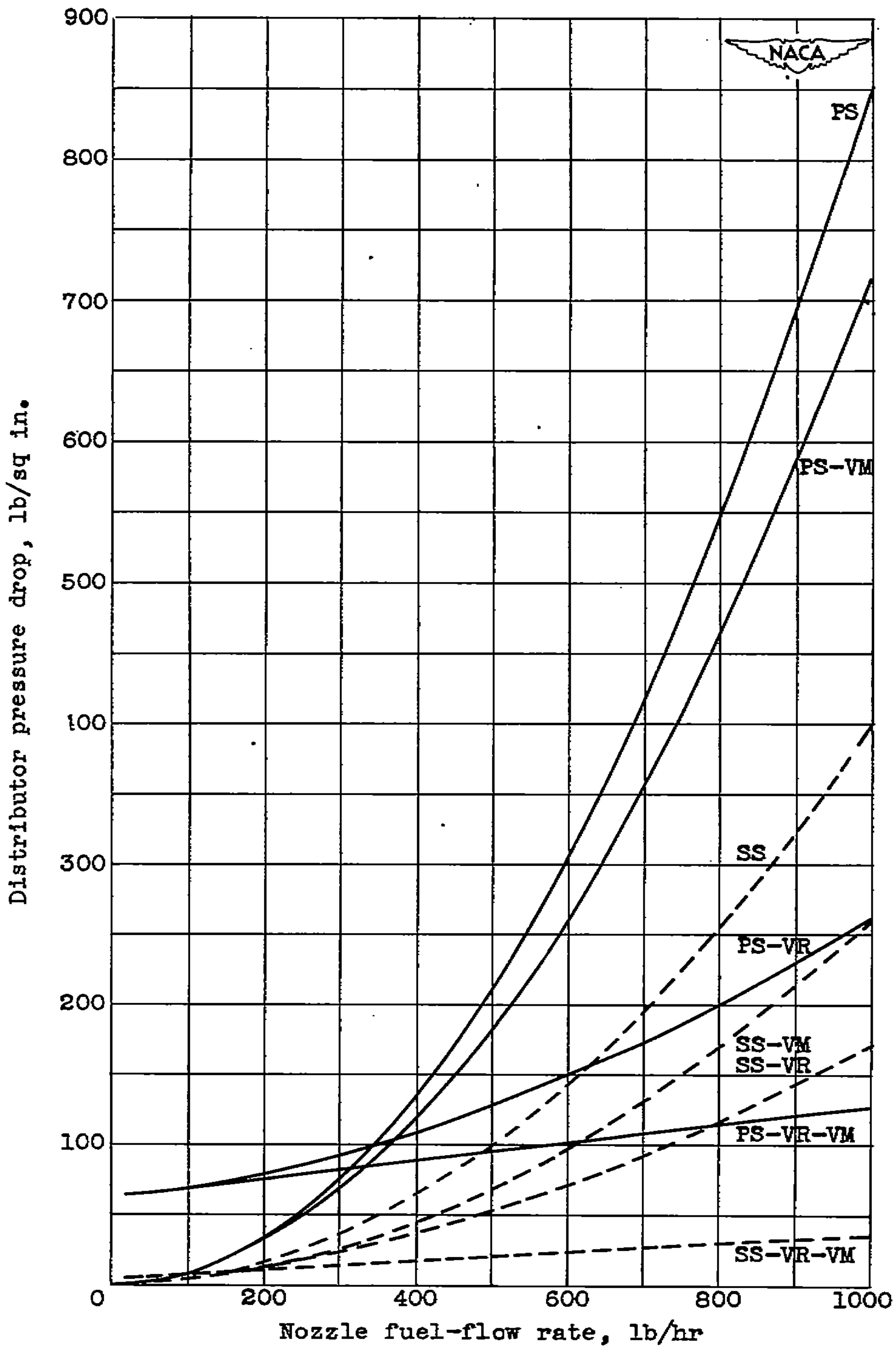


Figure 22. - Variation of distributor-pressure drop with fuel-flow rate per spray nozzle for eight fuel-distributor arrangements for same typical application conditions.

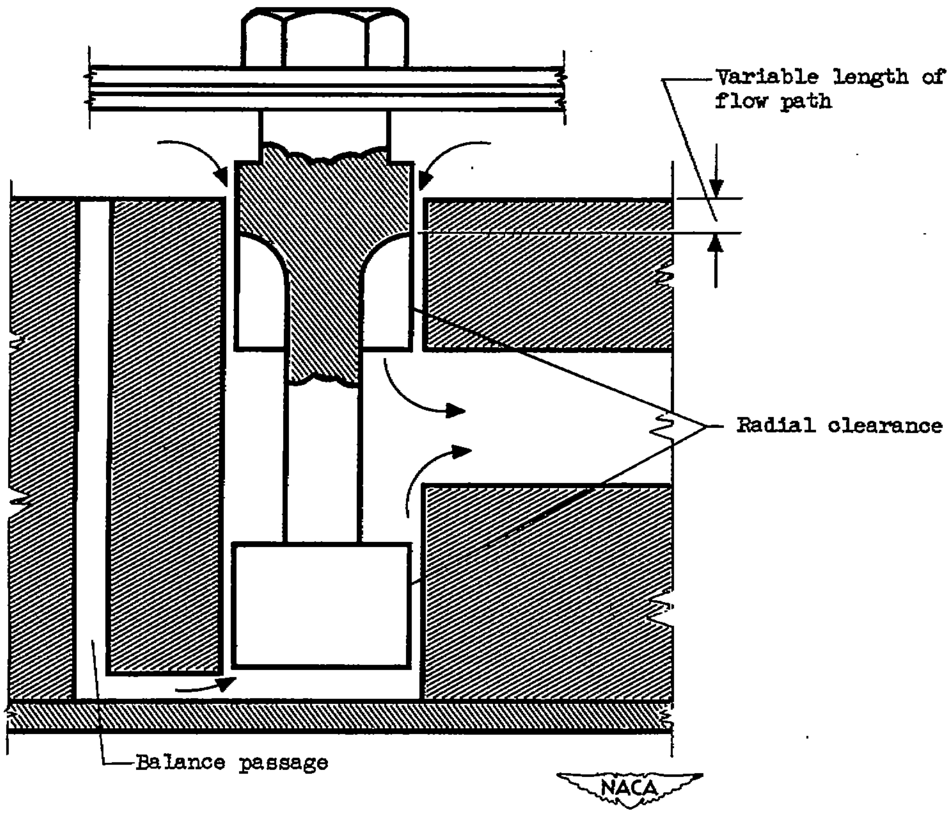


Figure 23. - Equalizing-valve construction including variable length of flow path.